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COMPARISON OF ON-BOARD AIRCRAFT
NICAD BATTERY CHARGERS

Joseph D. Dickinson

January 1980

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
A test was conducted at the Applied Technology Laboratory at Fort Eustis, Virginia to establish the performance characteristics of several on-board aircraft NiCad battery chargers. The test assessed performance characteristics of chargers from Utah Research and Development Company, Aerospace Avionics Corp., Eldec Corp., and Chrysler Corp. These performance characteristics were also compared to the battery performance associated with a simulated aircraft bus charging source. Adjunct tests investigated battery maintenance procedures.

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PREFACE

The Project Engineer for this test was Mr. Joseph D. Dickinson, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia. The test was conducted in-house at Fort Eustis during the period June 1978 through May 1979.

Other Applied Technology Laboratory personnel who contributed to the efforts documented herein were A. Williamson, N. Paxson, and D. Iannuzzi.

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INTRODUCTION

Over the last 20 years, a transition from lead-acid batteries to nickel-cadmium (NiCad) batteries has taken place in aircraft applications. The lead-acid battery was used because it provided an inexpensive and reliable power source for engine starting and electrical standby requirements. In addition, it could be charged safely and efficiently from the constant potential power source that was readily available in the form of the aircraft's DC bus. The lead-acid battery did not, however, have the power density capability to start a turbine engine at extremely low temperatures. A NiCad battery can provide the high discharge amperage and relatively constant voltage that is required for turbine engine starts down to approximately -25°F. Based on this low temperature/high amperage performance characteristic, the NiCad battery has exclusively replaced the lead-acid battery in U. S. Army aviation applications.

The transition from lead-acid to NiCad was accomplished with little regard for the effect that a constant potential charging source could have on the NiCad battery. As a result, incidents involving NiCad battery fires and explosions began to be reported as the transition progressed. Investigations into these reports revealed an unstable characteristic in the NiCad battery that is generally referred to as thermal runaway. The battery is said to be in thermal runaway when, under certain operating conditions, the following happens:

- An increase in battery temperature causes a decrease in the battery's internal resistance.

- The decrease in internal resistance allows increased charge current.

- The increased charge current further increases the battery temperature in a bootstrap fashion, resulting in a very rapid thermal failure.

It is generally agreed that two operating conditions are required for a thermal runaway to begin. First, the battery must be in its overcharge region and must be charging on a constant potential source that is capable of delivering high charge current. Second, the battery must be subjected to some condition that will elevate its temperature when it is in this overcharge region. One approach to a solution to this problem is to change the battery's charging source from constant potential to constant current. Using constant current, only a predetermined safe current level is permitted to be supplied to the battery regardless of what the battery demands. Taking advantage of this approach, numerous manufacturers have recently introduced on-board aircraft chargers that convert the aircraft's DC bus voltage into a constant current charging source. The list of manufacturers now includes: General Electric, Utah R&D, Aerospace Avionics, Marathon, Eldec, and Chrysler Space Division (the Chrysler chargers were developed under contract with Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, predecessor organization to ATL). All of these chargers effectively eliminate the threat of thermal runaway.

As these on-board chargers were being introduced onto the market, it became apparent that in addition to their primary function of eliminating the threat of thermal runaway, a secondary benefit could be derived from their use. That is, the battery's water usage

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rate and/or capacity retention rate could be improved by manipulating the charge profile. The on-board charger afforded the designer a wide range of choices for selecting an optimum charge profile. Each manufacturer now advertises increased service intervals and longer battery life. These claims are based on widely differing test conditions. As a result, a true comparison of how well one charger compares with the others, and how well all chargers compare with the DC bus charging source that is presently used in Army aircraft, is difficult to assess.

The intent of this test was to establish battery performance characteristics, both for water usage and capacity retention, associated with the use of selected on-board aircraft NiCad battery chargers. This was accomplished by exposing identical batteries to identical charge/discharge/rest cycles, and periodically taking capacity and water usage data until these characteristics were defined.

As the test progressed, two unanticipated battery characteristics were noted, which prompted additional testing that was not directly related to the main purpose of the test. The two adjunct tests involved investigations into the battery's capability to hold more water than is presently allowed by the maintenance manuals without spewage, and into the effect that reconditioning has or the battery's ability to maintain capacity. The results of these two adjunct tests are fully documented, along with the main test results, in the sections that follow.

This report describes the chargers that were tested, and presents the test procedures, the test results, and the conclusions and recommendations gleaned from the test. Supporting data are presented in Appendixes A and B. In addition, Appendix C is provided as a review of existing Department of Defense and NASA battery maintenance procedures and Appendix D provides some background on how the NiCad battery functions and how different charging techniques will affect its performance. A review of Appendixes C and D will clarify the terms used in the main body of this report.

CHARGER DESCRIPTIONS

The following chargers were selected for use in this test. They represent current state of the art in on-board chargers, and provide a good cross section of the performance characteristics that can be expected using such devices. The physical characteristics of each unit are shown in Figure 1 and Table 1.

Charger No. 1   Chrysler Space Division
        Part No. SKEE-751
        Serial No. P002 and P003
        DC input at 31.5V

Charger No. 2   Utah Research and Development Company
        Part No. ABC-28-10-1
        Serial No. 20-104 and 19-102
        DC input at 218V

Charge No. 3   Aerospace Avionics, Inc.
        Part No. 705565-819
        Serial No. 101 and 127
        DC input at 28V

Charger No. 4   Eldec Corporation
        Part No. 4-133-01 (modified)
        Serial No. 3 and 4
        AC input at 115V, 3Ø, 400 Hz

TABLE 1. PHYSICAL/FISCAL PROPERTIES OF CHARGERS TESTED

	Chrysler	Utah	Aerospace	Eldec
Weight (lb)	8.6	3.5	6.65	8.2
Volume (in.^{3})	346	144	170	313
Parts	242	147	not provided	100
Unit cost ($/100 units)	600	900	1200	650
Unit cost ($/1000 units)	475	800	950	620

NOTE: Each manufacturer advises that the above data will vary widely depending on a particular application.

a. Chrysler unit.
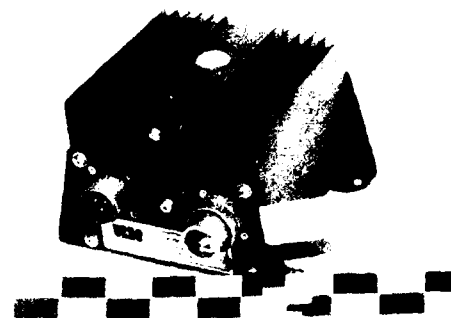
b. Utah unit.
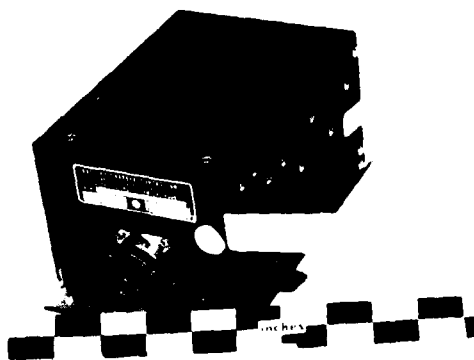
c. Aerospace unit.
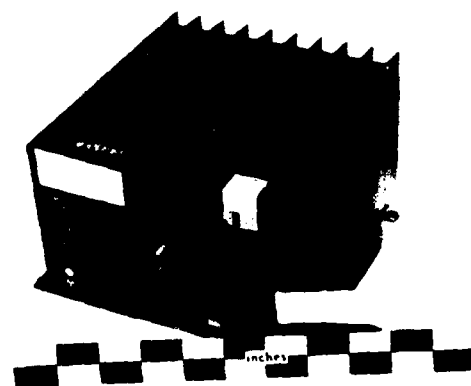
d. Eldec unit.

Figure 1. Chargers tested.

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In addition to the four chargers, a constant potential (no charger) setup was included to establish the battery performance associated with the dc bus charging method presently used in Army aircraft. Typical discharge/charge/rest profiles for each charging scheme are shown in Figures 2, 3, 4, 5, and 6. The discharge portion of the profile corresponds to the battery's voltage and current during an engine start, the charge portion corresponds to a typical bus charge during flight, and the rest portion corresponds to a between-flight shutdown or overnight rest. The following description of each profile further clarifies the information shown in each figure.

CONSTANT POTENTIAL (CP) (Figure 2)

This charge technique provides a very high initial current (approximately 41 amps) that is limited only by the internal resistance of the battery and, of course, by the power supply's current generating capability. As the battery is charged, its back-electromotive force (EMF) rises and approaches the EMF of the charging source. As the battery's back-EMF rises, the charge current diminishes and approaches zero as full charge is reached. The battery then "rides" on the bus for the remainder of the charge cycle. Using this charge technique, the battery performance is dictated by the voltage regulator setting. If the regulator is inadvertently set too low (below 28.5V at room temperature), the battery capacity will be less than optimum, and water consumption will be low. On the other hand, if the bus is set above 28.5V, battery capacity will be enhanced, but at the expense of high water consumption.
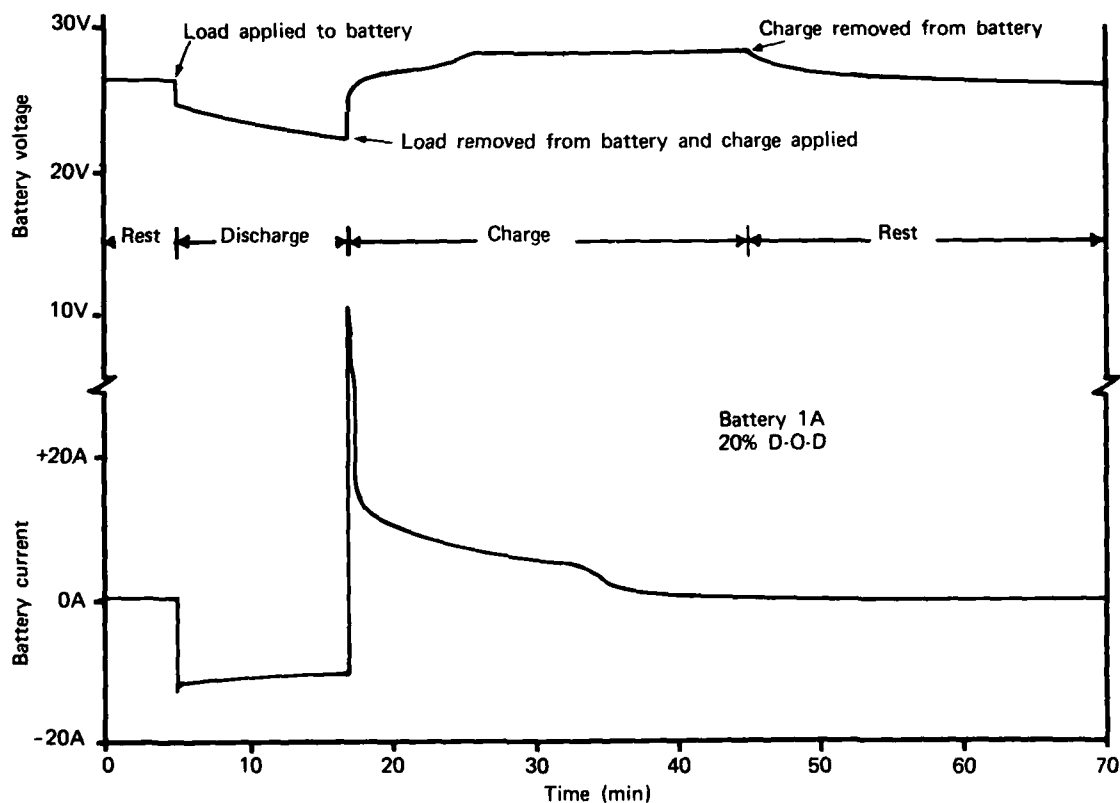
Figure 2. Charge profile for batteries on constant potential source.

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CHRYSLER CHARGER (Figure 3)

This charge technique limits the initial current to 11 amps until the battery voltage reaches approximately 28.5V. At this voltage level, the current is reduced to a second step of approximately 4.4 amps and maintained at this value until battery voltage reaches approximately 28.5V. At this voltage level, the current is reduced to a third step of approximately 1.1 amps and maintained at this value for the remainder of the charge cycle. The final battery voltage is dependent upon the magnitude of the applied power supply voltage. The power supply was set at 31.5V for this test, which resulted in an end-of-charge battery voltage ranging from 29.5V to 30.5V. Ordinarily, the Chrysler charger would boost the aircraft's bus voltage from 28V to 31.5V using an internal boost circuit, but during this test, the boosted chargers were not available. Accordingly, the power supply had to be set at 31.5V to compensate for the lack of the boosting circuit.
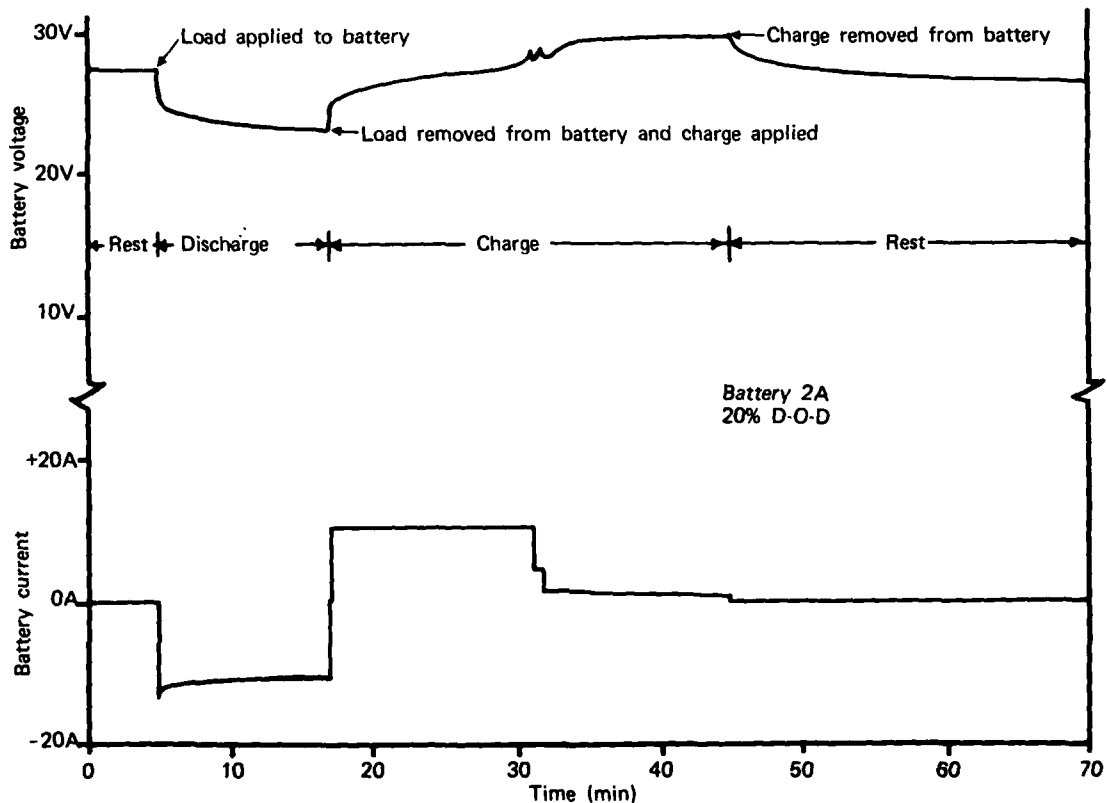
Figure 3. Charge profile for batteries on Chrysler charger.

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UTAH R&D CHARGER (Figure 4)

This charger initially maintains approximately 8.8 amps on the battery until battery voltage rises to 29.5V. At this voltage level, the current is reduced to a second step level of approximately 2.5 amps. This current is maintained until battery voltage rises to 30.5V. Charge current is then terminated until battery voltage diminishes to 27V, at which time the battery is current pulsed between 27.0 and 29.4V.
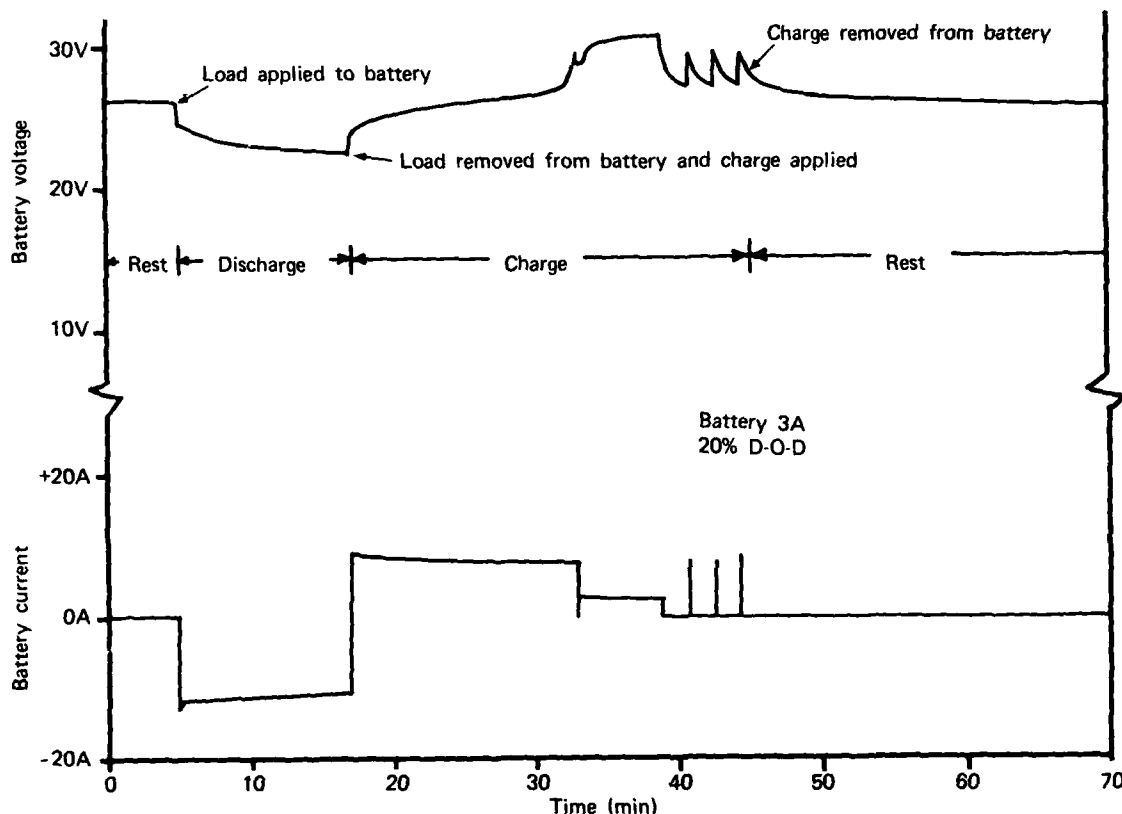
Figure 4. Charge profile for batteries on Utah R&D charger.

AEROSPACE AVIONICS CHARGER (Figure 5)

This charger maintains a high frequency pulse current between zero and 14 amps until the battery voltage reaches approximately 27.8V. At this voltage setting, the charger changes to a pulsed current varying between -4 amps and +14 amps. This current mode continues for the rest of the charge cycle. The frequency of current pulses diminishes as battery voltage reaches 28.8V.

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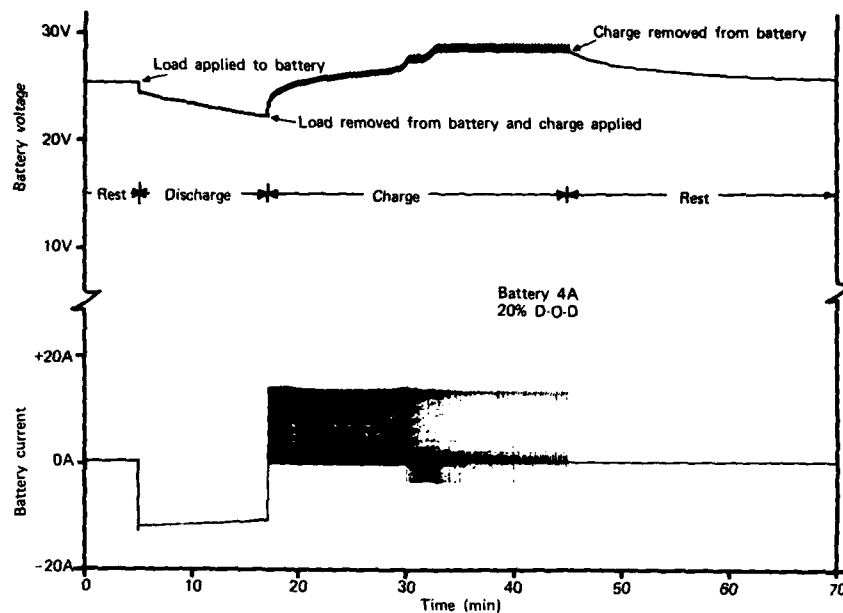
Figure 5. Charge profile for batteries on Aerospace Avionics charger.

ELDEC CHARGER (Figure 6)

This charger maintains 10 amps on the battery until battery voltage rises to 28V. At this voltage setting, the charger initiates a timed overcharge which is based on a fixed percentage of the main charge. When the proper percentage of overcharge is delivered to the battery, the charger terminates the charge.
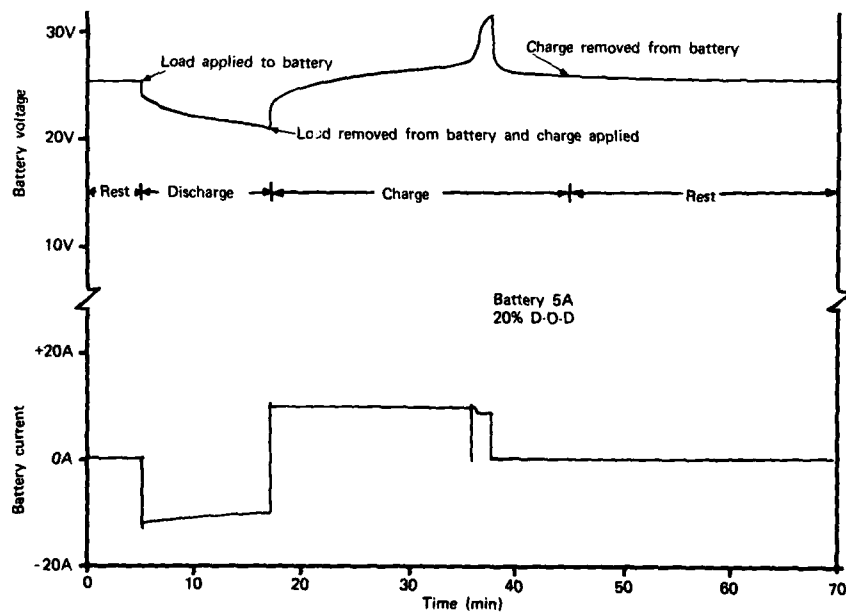
Figure 6. Charge profile for batteries on Eldec charger.

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TEST DESCRIPTION

The test was conducted on eight chargers (two from each manufacturer), and on two constant potential (no charger) batteries using new NiCad batteries. Each charger/battery test configuration, and the CP setup, was subjected to identical charge/discharge/rest cycles. At periodic intervals, capacity checks and water boil-off checks were taken to establish the performance characteristics of each scheme of charging.

The test was conducted in a well-ventilated testing facility that was maintained at a constant room temperature of $74^{\circ}F \pm 4^{\circ}F$. The general test setup is shown in Figure 7. Specific test setups are shown in Figures 8 and 9. The cycle test was automated, and ran 24 hours a day. The charge and discharge cycles were timed so that one power supply and one load bank could be used to cycle two test units. Originally, the test plan called for three different depths-of-discharge (D-O-D): 20%, 50%, and 100%. As the test progressed, however, it became obvious that the 50% D-O-D and the 100% D-O-D were too severe for this type of repetitive cycling. Accordingly, only the 20% D-O-D data is used in the body of this report. The 50% D-O-D data is included in Appendix B, but only for information purposes. The 100% D-O-D test was not attempted.

The 20% D-O-D was selected as representative of in-service use. This was based on the engine starting loads experienced in nine different helicopters. These loads ranged from 6% D-O-D to 25% D-O-D. The exact loading that the battery will be exposed to in field use is difficult to quantify. In many instances, false starts are encountered that can multiply the above figures by a factor of two or three. In other applications, the aircraft is started with ground power. Also, varying amounts of prestart checkout loads are imposed on the battery. After weighing all of the above, a 20% D-O-D was selected as a reasonable estimate that could be used to compare the test results with in-service usage.

20% DEPTH-OF-DISCHARGE TEST

Prior to starting this test, each battery was made ready for service by complying with an equivalent of para 5-3 of TM 11-6140-203-14-2 (Reference 1). Capacity was checked and recorded by discharging at 11 amps for the time required for the battery to reach a closed circuit terminal voltage of 19V; this time was recorded. After the capacity had been determined, the batteries were prepared for the start of the 20% D-O-D test by recharging and then adjusting the electrolyte level to 1/2 inch above the baffle after the battery had been allowed to rest for 3 hours. The cycle test was conducted in accordance with the profile presented in Table 2.

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[1] Technical Manual, TM -11-6140-203-14-2, *Operator's, Organizational, Direct Support, and General Support Maintenance Manual for Aircraft Nickel-Cadmium Batteries,* Department of the Army, Washington, D.C., 24 March 1978.

TABLE 2. 20% D-O-D PROFILE*

Function	Amps	Time	Volts
Discharge	11	12 minutes	Not less than 19V
Charge	Charger profile	28 minutes	Profile
Rest	0	30 minutes	Battery voltage

$$*20\% \text{ of rated capacity} = \frac{11 \text{ amps} \times 12 \text{ min}}{60} = 2.2 \text{ amp-hr}$$

During this test, the following parameters were recorded:

- Water usage at weekly intervals. Water level was adjusted to 1/2 inch above the baffle after charge and rest for 3 hours. The replenishment quantity of water was measured in cc.

- Capacity at weekly intervals. The 12-minute discharge cycle was interrupted and the capacity in ampere-hours was determined by recording the time required for the battery to discharge to 19V at the 11-amp rate.

The cycle test was continued until sufficient cycles had been accumulated to accurately define the chargers' performance characteristics. At the end of this test, the batteries were deep-cycle reconditioned in preparation for the next cycle test.
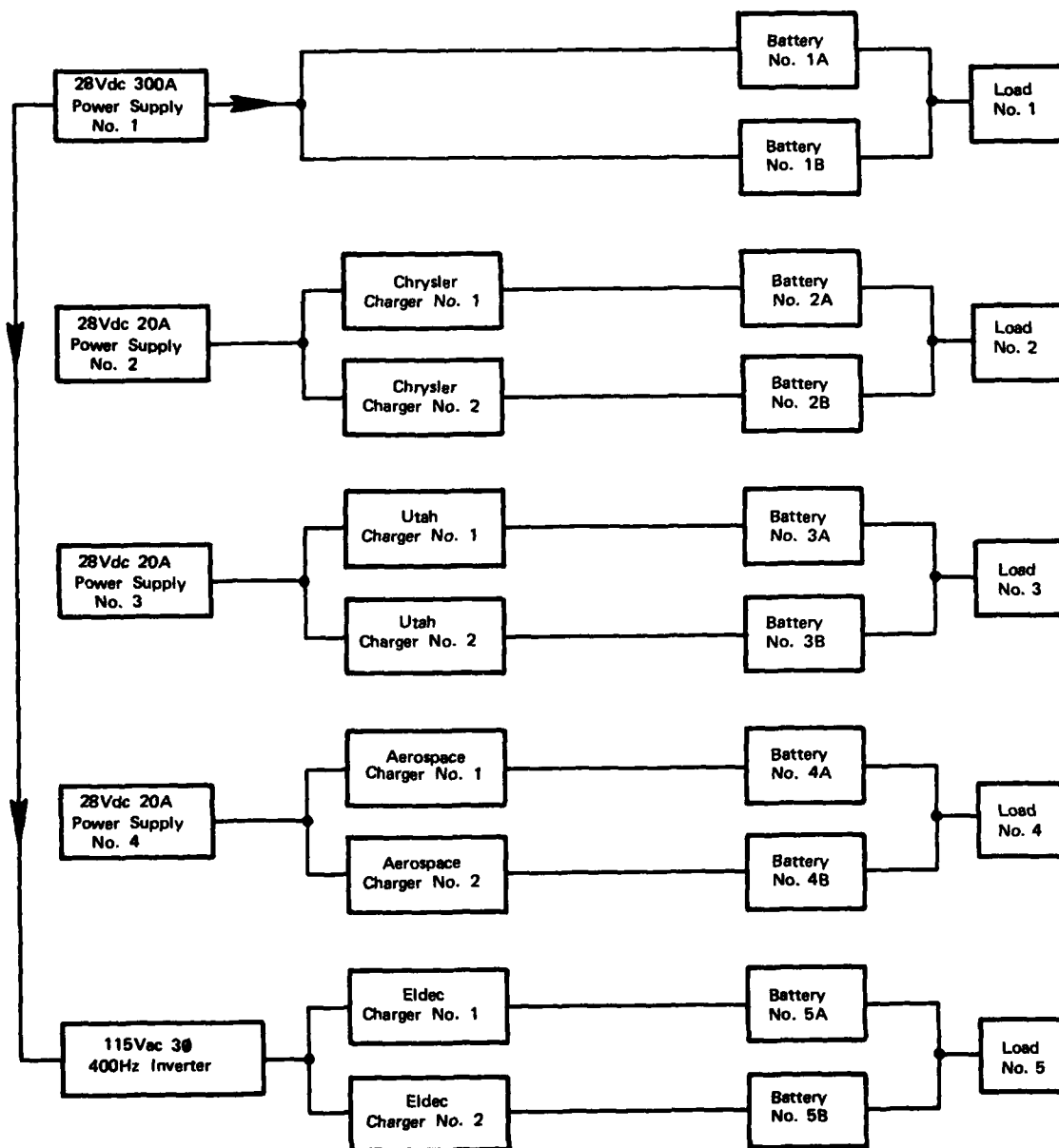
Figure 7. Overall charger test setup.
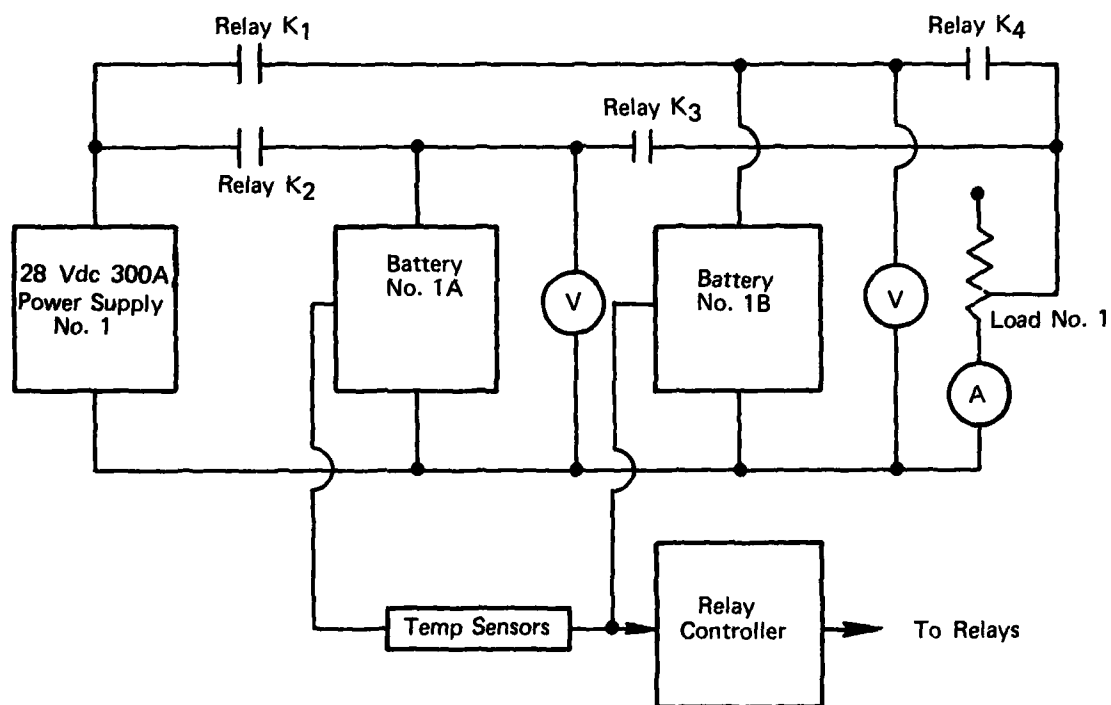
Figure 8. Test setup for constant potential cycle test.
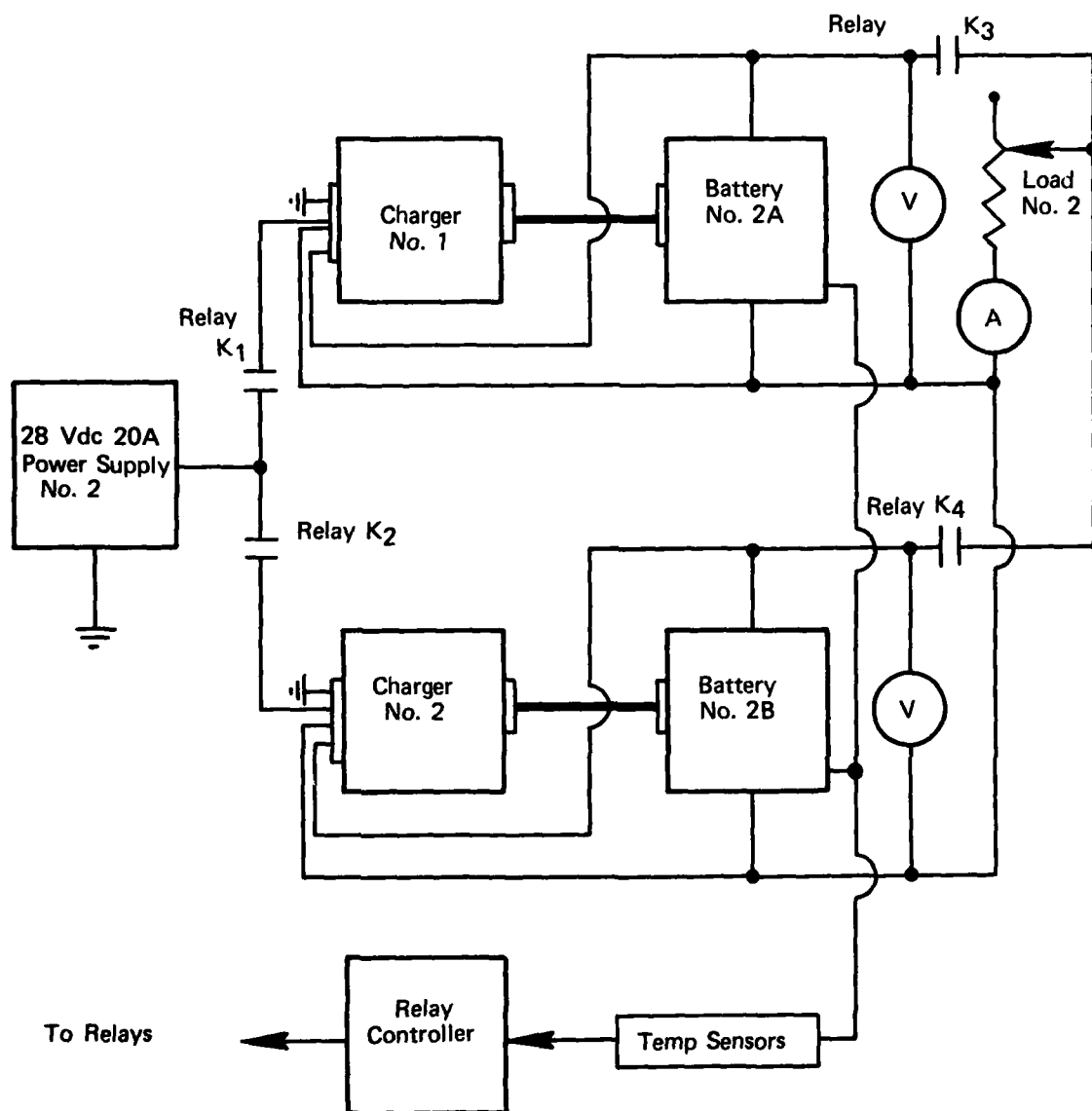
Figure 9. Test setup for charger cycle test.

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Power Supply Voltage Settings

During the course of this test, the open-circuit (no load) power supply voltages shown in Table 3 were used to power each charger. These settings were selected based on the charger manufacturer's recommendations. The constant potential power setting was selected based on aircraft bus voltage.

TABLE 3. POWER SUPPLY VOLTAGE SETTINGS

Charger	Voltage Setting
Constant potential (1st run)	28.4Vdc
Constant potential (2d run)	29.7Vdc
Chrysler	31.5Vdc
Utah	28.5Vdc
Aerospace	27.5Vdc
Eldec	115Vac

Battery Shop Maintenance

After each battery had been cycled through a sufficient number of cycles to establish its capacity and water usage characteristics, it was sent to the battery shop for a deep-cycle reconditioning. This process was intended to restore the battery's original capacity. The procedure used to recondition the batteries was as follows:

1. Disassemble and clean all hardware.

2. Reassemble and short all cells to zero volts (short is left on overnight).

3. Charge and overcharge until 18 amp-hr has been fed into the battery.

4. Check individual cell voltage during charge for any cell imbalance.

5. Discharge at 11 amps and ensure that voltage is maintained above 19V for at least 1 hour.

6. Ensure that cells are voltage balanced.

If battery voltage drops to 19V in less than 1 hour, repeat deep discharge process. If rated capacity cannot be restored after three attempts, scrap battery. If deep cycling restores capacity, final charge and overcharge to 18 amp-hr and adjust water level to 1/2 inch above top of plates after 3-hour rest.

DEVIATIONS FROM THE ORIGINAL TEST PLAN

The original test plan called for the following work to be accomplished in this sequence:

1. Procure 10 new batteries.

2. Make batteries ready for 20% D-O-D test.

3. Perform 20% D-O-D test, using two batteries each, on the CP, Chrysler, Utah, Aerospace and Eldec chargers.

4. Recondition 10 batteries and repeat test at 50% D-O-D.

5. Recondition 10 batteries and repeat test at 100% D-O-D.

As the test progressed, numerous deviations from the above planned sequence were required because of equipment failures involving power supplies, chargers, and test rig components. These deviations are documented and explained individually by battery and charger in the Test Results and Analysis section. As discussed above, the 50% and 100% D-O-D tests were deleted from the primary test plan.

It was also noted that each deep-cycle reconditioning appeared to produce a definite change in the battery's ability to retain capacity. Each time a battery was returned from the shop after reconditioning, its capacity appeared to fall off quicker than on the preceding test run. This implied that reconditioning cycles should be kept to a minimum, if maximum life was to be obtained from the battery. To further investigate this incongruity, additional tests were conducted on batteries 2A and 2B using the Chrysler chargers, on batteries 1A and 1B using the constant potential charger technique, and on batteries 5A and 5B using the Eldec chargers.

An additional deviation was made from the original test plan to investigate the proper amount of water that should be added to the battery when servicing is required. The Army technical manual requires water level adjustment to not more than 1/4 inch above the plates after the battery has been fully charged and allowed to rest for at least 30 minutes. Our test indicated that this water level could be increased without adverse effects, thus increasing time between servicings. In an effort to establish exactly how much additional water each cell would accept before spewing was noted in overcharge, another adjunct test was conducted that involved differing water levels and differing stages of charge and discharge.

TEST RESULTS AND ANALYSIS

GENERAL

This section presents the overall results that were obtained during the 20% D-O-D test. The capacity retention and water usage associated with each charging technique are shown in graphic form. Five charging techniques are shown: The constant potential (no charger) technique that is representative of an aircraft bus charge, the Chrysler multi-step constant current technique, the Utah multi-step constant current technique, the Aerospace pulsed or reflex technique, and the Eldec constant current technique. The performance associated with each of the five was derived using two batteries in each technique. The performance data collected for each pair of batteries have been averaged together to form a representative battery. This representative battery performance has been used in the graphs to show mean capacity retention and water usage. Appendix A shows the data that was recorded for each of the individual batteries tested.

PRIMARY TEST RESULTS

Batteries 1A and 1B were tested on the constant potential (no charger) test setup that was used to simulate an aircraft dc bus. Two runs were made with these batteries. The first run was made with the charge source set at 28.4V. This run represented a typical in-service exposure with the aircraft voltage regulator properly set. The performance characteristics for this run are shown in Figure 10. (The dashed line indicates anticipated water usage had the test run been continued beyond 572 cycles.) A second run was made with these two batteries, but this time the charge source voltage was increased to 29.7V. This represented an in-service exposure to an aircraft voltage regulator that is set too high. This run is shown in Figure 11. Battery performance using the Chrysler charger is shown in Figure 12. Battery performance using the Utah charger is shown in Figure 13. Battery performance using the Aerospace charger is shown in Figure 14. Battery performance using the Eldec charger is shown in Figure 15.

A composite graph showing the battery performance of all five charge techniques is shown in Figure 16. For ease of comparison, the capacity line of each technique shown in the composite graph has been adjusted to a common intercept of 11 amp-hr. The slope of each line has been maintained in all cases. This graph shows the relative battery performance that can be expected using any one of the charge techniques tested. It indicates that the chargers provide better capacity retention than the CP technique, but that the CP technique uses less water if the voltage regulator is properly set at 28.4V. If the voltage regulator is inadvertently set too high, as is the case at 29.7 V, water usage increases dramatically. This situation quickly results in a dry battery and associated thermal problems. The chargers compensate for incorrect bus settings, and therefore eliminate the possibility of high voltage boil-off.

A specific example of water and capacity performance that can be expected using any of the five charging techniques is shown in Table 4.

TABLE 4. BATTERY RECONDITIONING AND WATER REPLENISHMENT PERIODS

Charger Technique	Recondition at (weeks)	Water at (weeks)	
		1/4-in. level (133 cc)	1/2-in. level (266 cc)
Eldec	200 (extrapolated)	36	44
Chrysler	50	27	38
Utah	28	21	28
Aerospace	12.6	40	57
CP at 28.4 V	12.4	83 (extrapolated)	90 (extrapolated)
CP at 29.7V	9.0	10	16

The example shown in Table 4 uses a typical operating schedule of 10 engine starts per week (2 starts per day, 5 days per week). It is assumed that no ground power unit starts are made, and that each start is successful on the first attempt. The reconditioning time is established at 8.8 amp-hr or 80% of the battery's rated capacity. Also, time-to-water is given at two different water head levels (1/4 in. and 1/2 in.). It should be noted that the CP run at 29.7V was conducted on used batteries (they had been run at 28.4V prior to this run). It is believed that a much greater capacity retention would have been recorded had new, never used batteries been run at 29.7V.
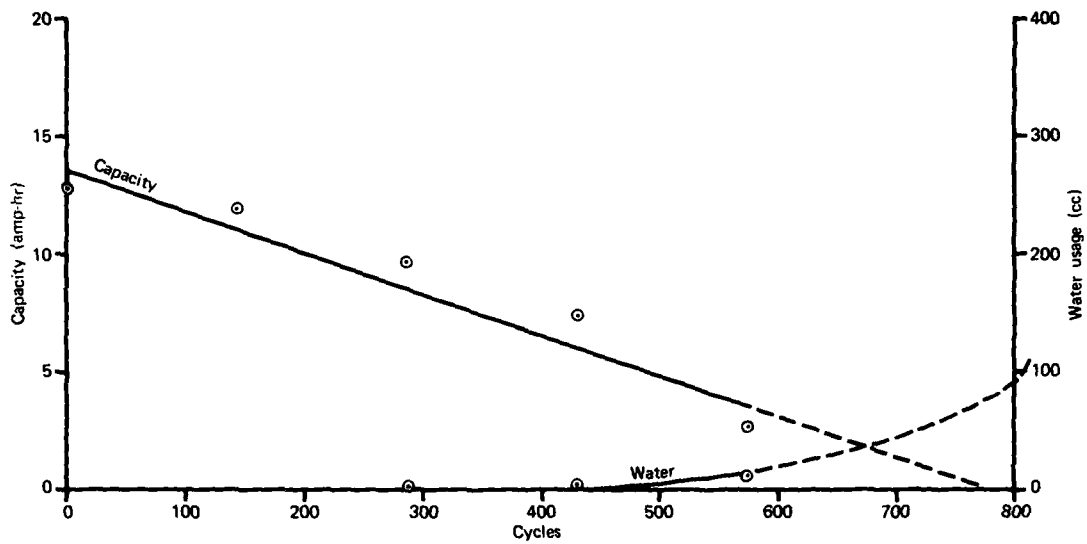
Figure 10.   Constant potential battery performance — 20% D-O-D — 28.4V.
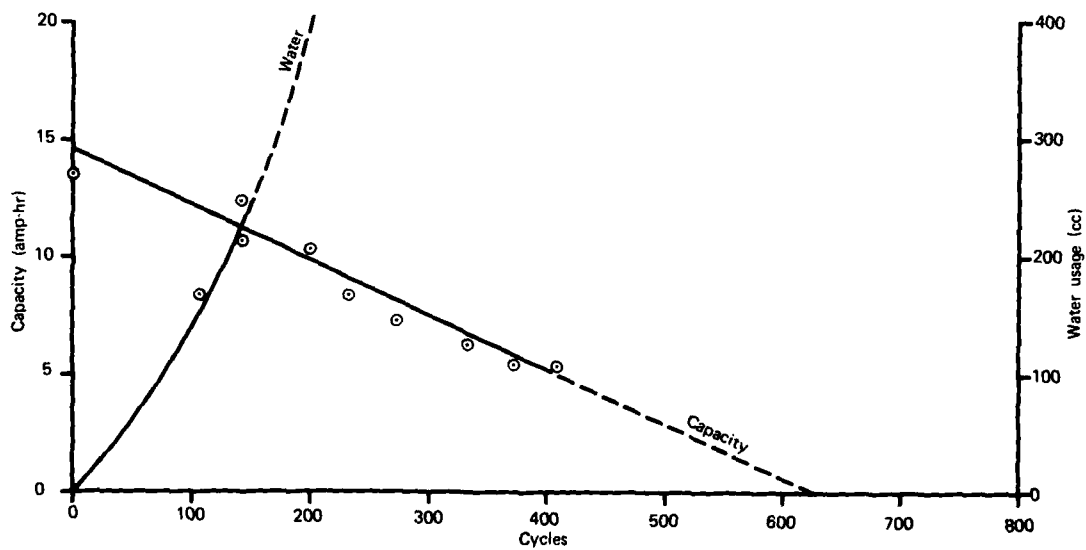
Figure 11.   Constant potential battery performance — 20% D-O-D — 29.7V.

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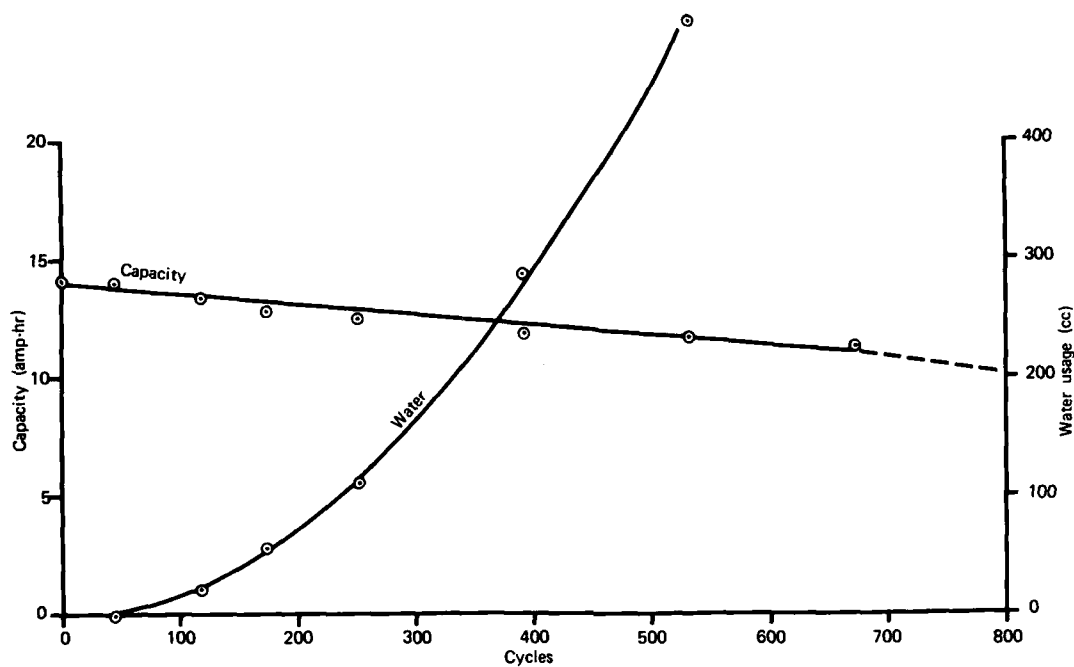
Figure 12.   Chrysler charger battery performance — 20% D-O-D.
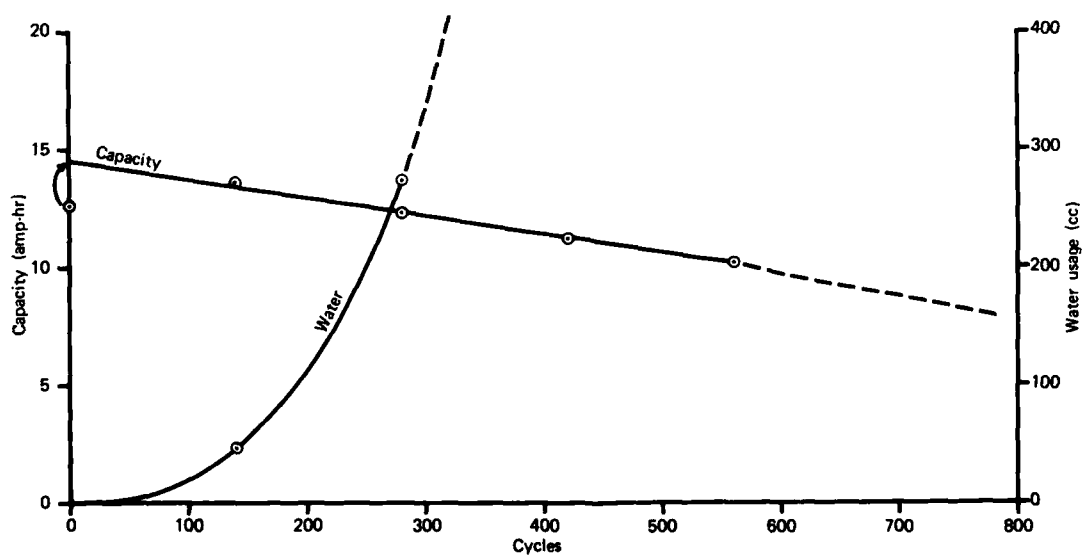
Figure 13.   Utah charger battery performance — 20% D-O-D.

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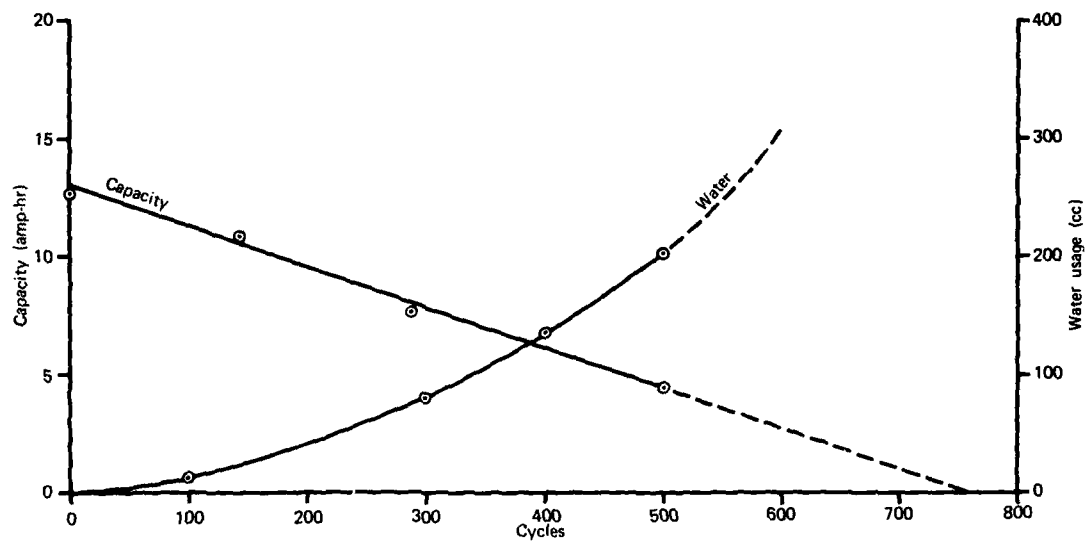
Figure 14. Aerospace charger battery performance — 20% D-O-D.
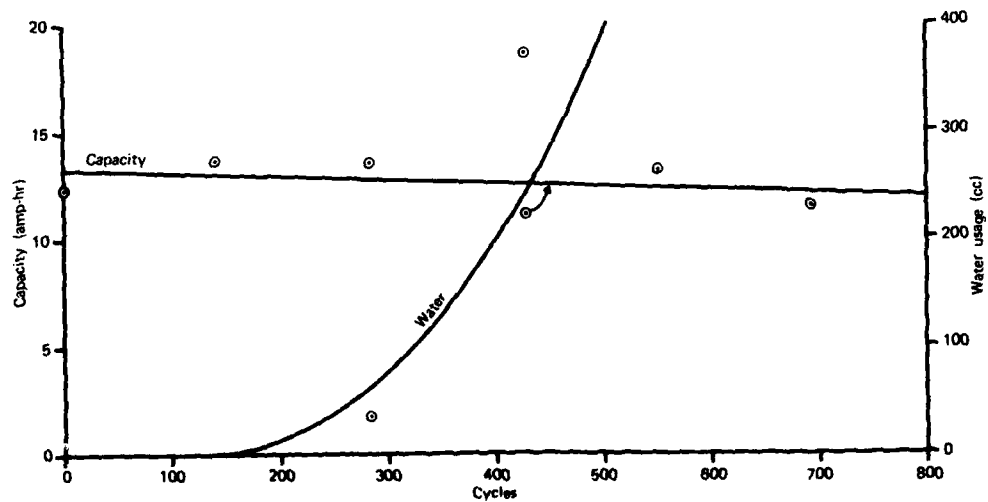
Figure 15. Eldec charger battery performance — 20% D-O-D.
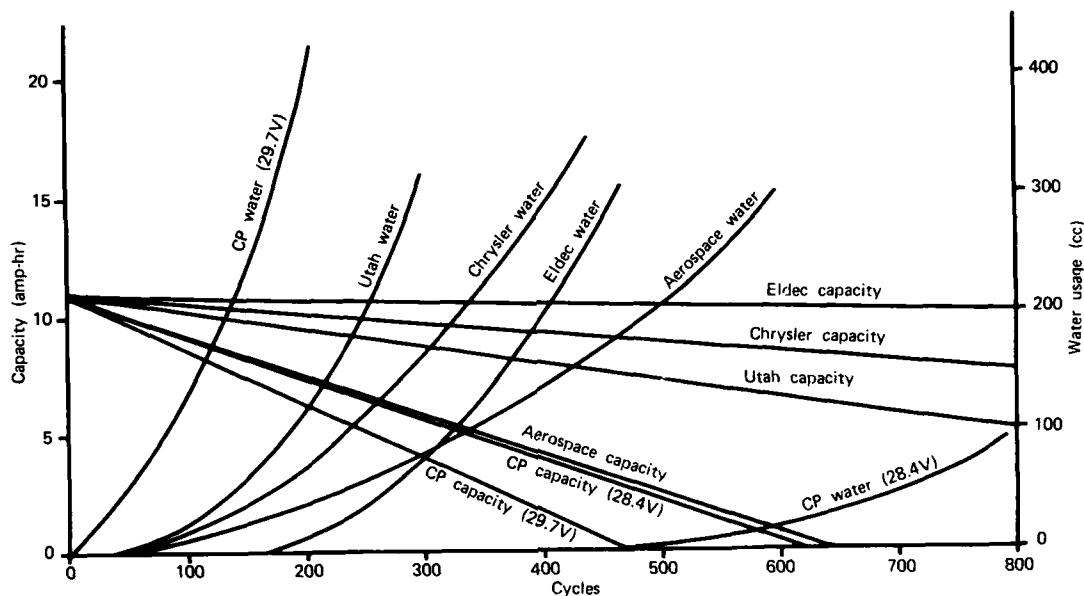
Figure 16. Composite of all chargers' performance — 20% D-O-D.

ADJUNCT INVESTIGATIONS

In addition to determining the basic performance characteristics of each charging scheme, two adjunct investigations were conducted.

Deep-Cycle Reconditioning Effect On Capacity

The first investigation involved determining what effect deep-cycle reconditioning has on capacity retention. This test was accomplished after it was discovered that batteries 6A and 6B exhibited a more abrupt capacity fall-off following each return from the battery shop after reconditioning. The average capacity lines of batteries 6A and 6B are shown in Figure 17. These lines were recorded at the 20% D-O-D level. The first run was made when batteries 6A and 6B were new (never used) and was terminated after 251 cycles due to a power supply failure. The second run was made after the batteries had been deep-cycled and was terminated after 358 cycles due to low capacity. The third run was made after the batteries had been deep-cycled, and ran for 221 cycles prior to experiencing low capacity. It should be noted that between the second and third 20% D-O-D runs, as shown in Figure 17, a 50% D-O-D run had been accomplished on batteries 6A and 6B. Individual capacity readings for batteries 6A and 6B are shown in Table A-14.

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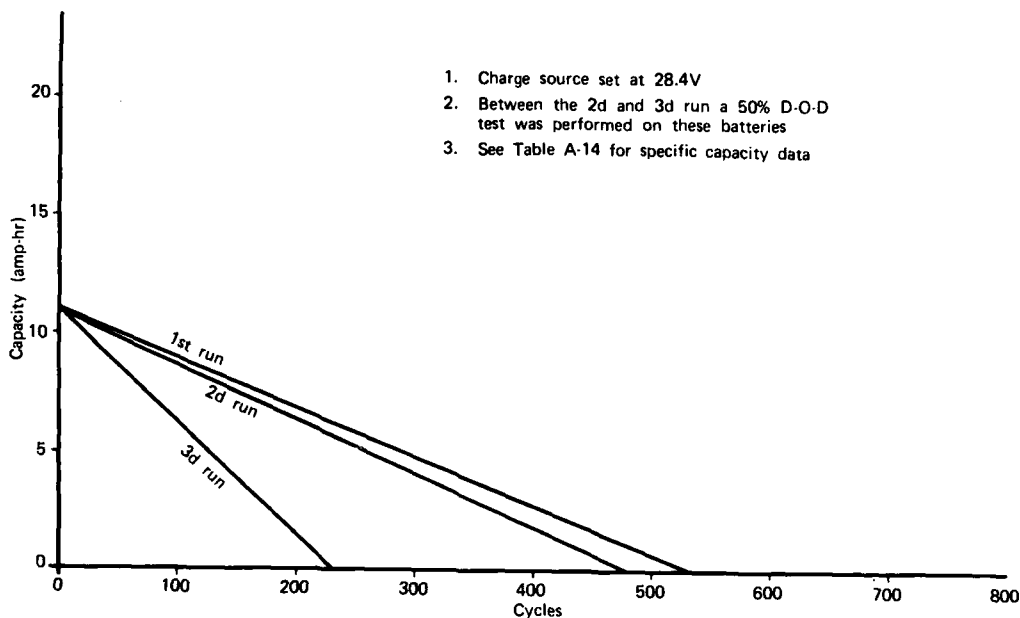
Figure 17. Capacity falloff versus deep-cycle reconditionings,
constant potential batteries 6A and 6B — 20% D-O-D.

After this trend was noted on batteries 6A and 6B, an identical test was conducted
using the Chrysler charger batteries 2A and 2B to determine if they would exhibit the
same trait. Three runs at the 20% D-O-D level were accomplished with a deep-cycle
reconditioning process between each run. The first run was accomplished when
batteries 2A and 2B were new (never used) and logged 672 cycles prior to termination.
After the first run, 2A and 2B were deep-cycled and run at the 50% D-O-D level for
98 cycles before low capacity was encountered. Following the 50% D-O-D run, the
batteries were deep-cycled and the second 20% D-O-D run was made. This run lasted
through 287 cycles before low capacity was encountered. The third run was made
after another deep cycle, but Chrysler charger No. 1, associated with battery 2A, failed
shortly into this run. Accordingly, only battery 2B and its interconnected Chrysler
charger were recorded during this third run. Figure 18 shows the average capacity
characteristics of batteries 2A and 2B during these tests. Individual capacity data are
shown in Table A-14.

At this point in the test, it appeared obvious that the deep-cycle procedure was, in
some way, weakening the battery's ability to maintain capacity. There was, however,
one other possible contributor to weak capacity that had not been assessed, namely
the effect that the 50% D-O-D run that had been accomplished beween the 20% runs
might have had on the battery's ability to maintain capacity. To assess what effect,
if any, the 50% D-O-D run had contributed to this capacity behavior, two additional
tests were conducted. These tests were accomplished using batteries that had not been

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cycled at the 50% D-O-D level. Batteries 1A and 1B, and batteries 5A and 5B, were selected for use in this test. Batteries 1A and 1B had both been run at the 20% level at 28.4V, reconditioned, and then run at 29.7V as shown in Figures 10 and 11. The 28.4V run involved 574 cycles and the 29.7V run consisted of 208 cycles. Batteries 1A and 1B were reconditioned for the second time and run at the 20% D-O-D at 29.7V. Results of this run are shown in Figure 19. Batteries 5A and 5B had been cycled with the Eldec chargers at the 20% D-O-D level for 692 cycles as shown in Figure 15. These batteries were reconditioned and run at the 20% D-O-D level using the Eldec chargers. The results of this run are shown in Figure 20. Individual capacity data are shown in Table A-15.

1. Charged IAW Chrysler profile
2. Between 1st and 2d run, a 50% D-O-D test was performed on these batteries
3. See Table A-14 for specific capacity data
4. The 3d run was made on battery 2B only, 2A charger failed at the end of the 2d run.
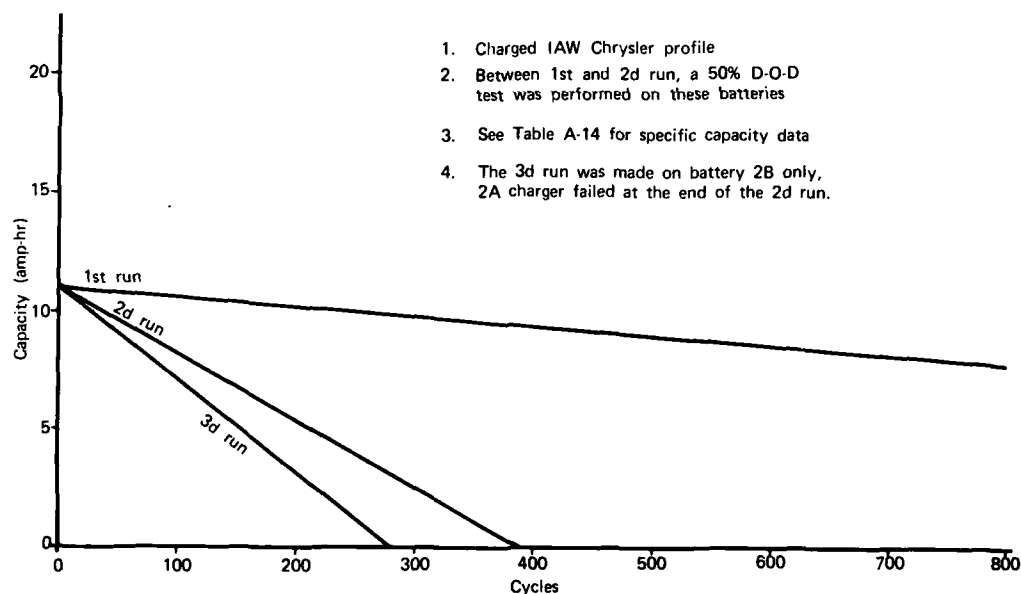
Figure 18. Capacity falloff versus deep-cycle reconditionings, Chrysler charger batteries — 20% D-O-D.
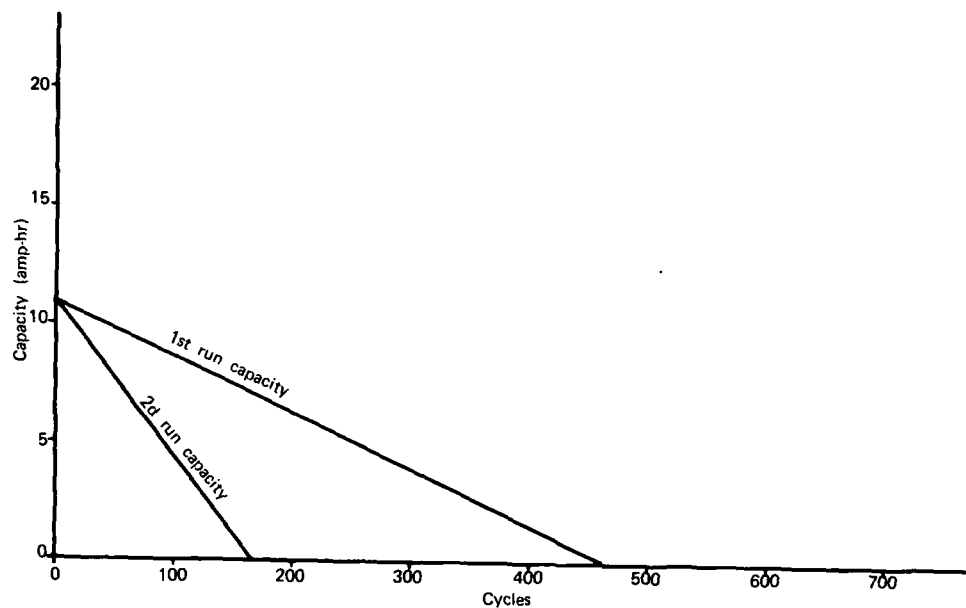
Figure 19. Capacity falloff versus deep-cycle reconditionings, constant potential batteries 1A and 1B — 20% D-O-D (29.7 volts).
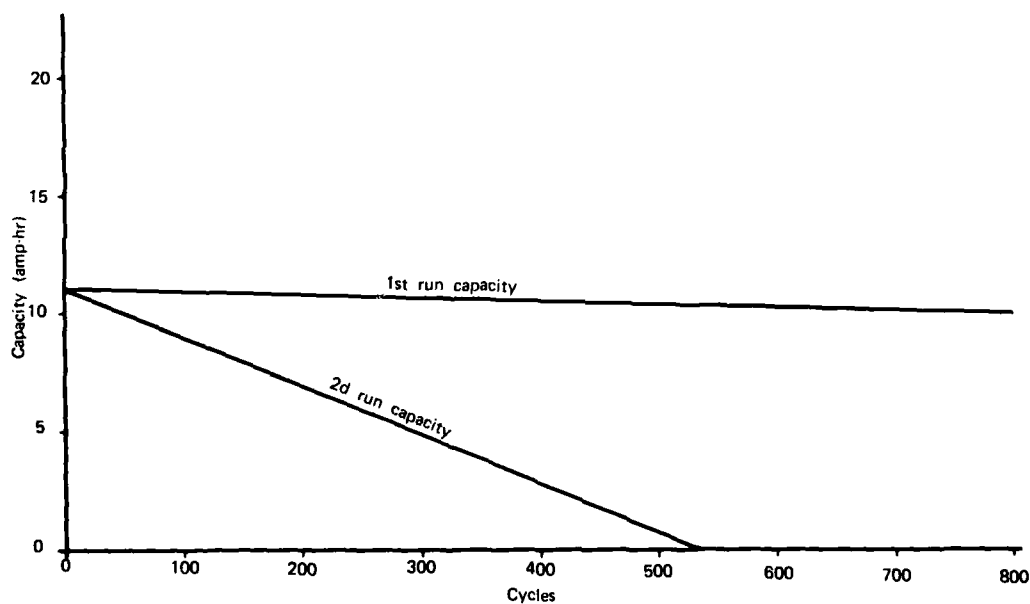
Figure 20. Capacity falloff versus deep-cycle reconditionings, Eldec charger batteries — 20% D-O-D.

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Battery Water Level Investigation

The second adjunct investigation involved water servicing procedures and especially the Army's requirement to service the battery water level to not more than 1/4 inch above the plates after a 30-minute rest period following full charge. This investigation was prompted by the fact that the batteries appeared to have the capacity to hold a much greater quantity of water than the 1/4-inch limit allowed. As pointed out in Appendixes C and D, the head space available above the plates in the BB-432/A batteries used in this test measured approximately 2 inches in height. Of this 2-inch head space, only 1/4 inch can be filled with electrolyte according to existing publications. If the battery can, in fact, accommodate more water than the 1/4-inch restriction allows, less frequent servicing intervals can be established. Accordingly, this test was accomplished to establish the highest allowable water level for the battery.

The test was conducted considering the following factors: (1) *The cell plates must be* covered with water at all times. (2) The water level ebbs as the battery is discharged; the lowest possible level is encountered in a deep-discharge and rest condition on a battery with a low state of charge. (3) The battery will spew water through the vent caps in overcharge if the water level is set too high, or may leak electrolyte through the caps in overcharge during semi-inverted flight.

Battery 2B was selected for this test because it was in a low state of charge; only 1.5 amp-hr remained in the battery at the start of this test. The battery was rotated through a pitch and roll attitude of 75 degrees and the water level that just cleared the bottom of the vent cap at these attitudes was measured. It was determined that 1 inch of head space could be filled under these conditions. Next, the battery was fully charged using the Chrysler charger and the water level was adjusted to 1/2 inch above the plates. The battery was then rested and discharged, and the following water levels were observed.

Time	Water Level (in.) (above plates)
Immediately after charge	0.5
After 3-hour rest from charge	0.25
After 12-minute discharge	0.25
After 3-hour rest from discharge	0.25
After overnight rest	0.125
After another overnight rest	0.25
After resting for 4 more days	0.125

Based on the above, it appeared that the battery had the capacity to accommodate a 1-inch water head, instead of the 1/4-inch head as presently specified. Also, even if *the battery were inadvertently serviced to the 1-inch level with the battery in a dis-* charged and rested state, the water level would rise to only 1-3/8 inch above the plates when brought to a fully charged state. Under those conditions, an unfilled head space of 5/8 inch (2 in. -1-3/8 in.) remained that would accommodate a roll or pitch angle of approximately 60 degrees before the bottom of the vent plug would become covered with water. It was believed that the possibility of overservicing, high attitude angle, and overcharge occurring simultaneously for any appreciable period of time was remote enough to justify selection of the 1-inch water head as a trade-off against more frequent

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water servicings. The last consideration was the possibility of spewage in overcharge using the 1-inch water head. To assess the degree of spewage in overcharge, the following test was accomplished. The water level in battery 2B was adjusted to the 1-inch level immediately after full charge using the Chrysler charger. The battery was then transferred to the constant potential charging cabinet. The battery was overcharged at voltage levels up to 31.6V. At voltage above approximately 28V, hydrogen and oxygen gassing began and the cells gassed freely at 31.6V, but no electrolyte spewage was noted at any of the above voltages.

CONCLUSIONS

Conclusions have been drawn from the main test results and from the adjunct test results. These conclusions have been separated into two groups: the first group relates to charger performance in the main test; the second group relates to battery maintenance practices (the adjunct tests).

CHARGER PERFORMANCE

1. All of the chargers tested provided better capacity retention than did the constant potential charge technique that was used to simulate an aircraft dc bus charge. When the constant potential charge technique was correctly set at approximately 28.4 V, the constant potential batteries used less water than did the charger batteries. When the constant potential voltage was incorrectly set at 29.7 V, the constant potential batteries used more water than the charger batteries.

2. Incorrect dc bus voltage settings can be caused by improper maintenance actions, or by changes in ambient temperature. If maintenance personnel set the regulator too high, battery water usage will increase; if too low, battery capacity will be weak. Ambient temperature changes have the same effect. If the voltage regulator is set properly and temperature increases, water usage increases; if temperature decreases, capacity retention decreases. This variability in charge voltage makes it difficult, if not impossible, to establish a realistic maintenance schedule. Because the threat of high voltage charging is always present when charging from the dc bus, overservicing is justified and, in fact, prudent, considering the safety implications associated with thermal runaway from an overcharged battery. All of the chargers tested have compensating circuitry that eliminates this threat. They operate over a band of bus voltages and provide the proper charging voltage regardless of the value set by maintenance personnel. In addition, temperature changes are automatically compensated for and the optimum voltage-versus-temperature relationship is applied to the battery. These two factors afford a considerable extension in both water and reconditioning servicing intervals.

3. The optimum charger should return just enough current to convert all of the available active material in the plates of each cell back to a 100% charged condition, because any current returned to the battery cells after all available active material has been converted is wasted as electrolyte boil-off. In addition, the optimum charger should return the charge in a minimum of time, and should control the current flow into the battery when in overcharge. To construct a charger that incorporates all of these features is impractical. Further, airborne applications require minimum weight, power, and volume, and maximum reliability and maintainability. Accordingly, trade-offs must be made so that the charging process is as efficient as possible within the constraints imposed by the operating vehicle.

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When optimum features are traded for weight, volume, and cost, the battery's ability to maintain capacity or use water is affected. The overcharge current control capability should not be subject to trade-off, since it is related to safety and thermal runaway, and should be a mandatory feature of any charging technique.

4. All of the chargers tested operate on a constant current principle, and therefore control the overcharge current flow. In addition, all chargers tested incorporate thermal detection devices that terminate all charging action when an overtemperature condition develops. Thus, the hazard associated with thermal runaway is eliminated using these chargers. The constant potential charge technique cannot effectively control overcharge current on a consistent basis. As explained in Appendix D, a battery under charge is operating in accordance with the equation $E_{PS} = E_B + Ir$, where E_{PS} = power supply voltage, E_B = battery voltage, I = charge current, and r = internal battery resistance. If the internal resistance of the battery diminishes, and the charging potential is held constant, the charge current will increase. An increasing charge current relates to increasing battery temperature and the threat of thermal runaway.

5. Of the chargers tested, only the Utah and Eldec units terminate the charge after a preselected amount of the previous discharge has been returned to the battery in charge and overcharge. This is a desirable feature that should be incorporated in all chargers. In both the Utah and the Eldec, the amount of return charge is based on a fixed percentage of the time that the charger was in its main charging mode. Utah R&D literature indicates that a 115% return of previous discharge is provided, but states that this figure can be adjusted between 110% and 140% depending on the application involved. Data collected during this test showed that approximately 110% was returned to the battery. Eldec literature is not specific on the amount of return charge. However, more charge is returned using the Eldec unit than with any other technique tested. Data collected during the test indicates that approximately 154% of the previous discharge was returned in charge. The Chrysler and Aerospace units do not time the amount of return charge. With these units, the amount of return charge depends on the length of the charging cycle, which relates to flight time. As long as the generators are powering these chargers, additional current will be pumped into the battery. Accordingly, using these units, the battery may be undercharged or overcharged, depending on the length of the flight that follows a battery discharge. This method does not provide a consistent control mechanism such as is provided with the Utah and Eldec units.

6. The Utah R&D charger exhibits the best <u>physical</u> characteristics of the chargers tested. It weighs less, occupies less space, and produces less heat.

7. The Eldec charger provides the best <u>performance</u> characteristics based on its ability to maintain the battery's capacity at the highest level while using only moderate amounts of water.

BATTERY MAINTENANCE

1. Using an on-board charger, the weekly water check requirement that presently exists in Army maintenance manuals can be eliminated. Also, time between deep-cycle reconditionings can be greatly extended.

2. Using an on-board charger, the water level adjustment can be increased. This permits more excess water to be carried, which results in less frequent water servicings. This test indicated that the water head level in the BB-432/A battery can be increased by a factor of 4.

3. Deep-cycle reconditioning should not be accomplished on a routine basis. If more than 80% of the battery's capacity is remaining during the battery shop inspection, the battery should be returned to service. The time between deep cycles will have to be adjusted downward as the battery ages and its capacity falloff becomes more and more abrupt.

4. During the course of this test, while reviewing the numerous publications that apply to NiCad battery performance and maintenance, it was noted that TM 11-6140-203-15-1 (Reference 2) and TM 11-6140-203-14-2 do not require a specific gravity check on the electrolyte during shop maintenance. In addition, no procedure for changing or adding electrolyte is provided. Although this observation is removed from the primary intent of this investigation, it is believed that this report is an appropriate place to cite this omission as a supplementary conclusion. These checks and procedures should be provided in the maintenance publications. As cited in Appendix D, the electrolyte concentration will diminish as boiled-off water is replenished during servicing. If the specific gravity falls below 1.23, an otherwise good battery will not pass a capacity check and may be discarded. The specific gravity should be checked during shop servicing intervals. In addition, the procedure for flushing contaminated electrolyte and adding fresh electrolyte is needed. Also, if the battery is inadvertently tipped and electrolyte is spilled, a procedure to replenish the spillage is required.

[2] Technical Manual, TM 11-6140-203-15-1, *Operator, Organizational, Direct Support, General Support, and Depot Maintenance Manual: Aircraft and Nonaircraft Nickel-Cadmium Batteries*, Department of the Army, Washington, D.C., 1 December 1969.

RECOMMENDATIONS

1. All Army aircraft that employ a NiCad battery should be equipped with an on-board charger. A charger will enhance battery performance, battery life, and aircraft flight safety.

2. When selecting the best charger for use in Army aircraft, man-hours expended for battery maintenance should be a prime consideration along with weight, volume, parts count, and price. Each charger manufacturer should be required to provide performance characteristics based on a common 20% depth-of-discharge cycle.

3. The charger should compensate for the battery's charge inefficiency by returning 140% of the previously discharged capacity in a minimum of charge time (flight time). After 140% of discharge has been returned to the battery, the charge should be terminated. After termination of the main charge, a trickle charge or pulsed topping charge should be applied to compensate for the battery's self-discharge characteristics and to keep the battery in a high state of readiness.

4. Only temperature compensated, boosted DC chargers should be considered for aircraft applications.

5. Routine deep-cycle battery reconditioning is not recommended. If a capacity check reveals that the battery has sufficient capacity remaining and the battery meets all other maintenance requirements, the battery should be returned to service.

6. The water level adjustment limit should be reexamined for each battery type to determine if additional head space can be used to carry excess electrolyte. It is recommended that the electrolyte level be increased from 1/4 inch to 1 inch above the plates in the BB-432/A battery that was used in this test.

7. The specific gravity of the electrolyte should be checked during battery shop maintenance. If the specific gravity does not fall within the required limits, electrolyte or pure water should be added or removed as appropriate. Also, if electrolyte contamination is suspected, the battery should be flushed and refilled with fresh electrolyte.

APPENDIX A
20% DEPTH-OF-DISCHARGE TEST DATA

The 20% depth-of-discharge tests measured battery water usage and capacity at weekly intervals. Tables A-2 through A-13 present data for batteries charged by a simulated aircraft constant potential bus and by the four tested battery chargers. These data are graphically depicted in Figures A-2 through A-7. The number of recorded test cycles varied for individual batteries; readings were terminated when sufficient data was accumulated to accurately define the characteristics of the several charge sources. Tables A-14 and A-15 present data on the effects of repeated deep-cycle reconditioning processes.

TABLE A-1. BATTERY DATA

BATTERY NO.	SERIAL NO.
1A	7701106
1B	7701100
2A	7701241
2B	7701184
3A	7701220
3B	7701219
4A	7701156
4B	7701270
5A	7700985
5B	7701008
6A	7701343
6B	7701319
7A	7701137
7B	7701340
8A	7701236
8B	7701248

Marathon Battery MA-7
BB-432A 11 amp-hr
24 V, 19 cells
New, never used batteries
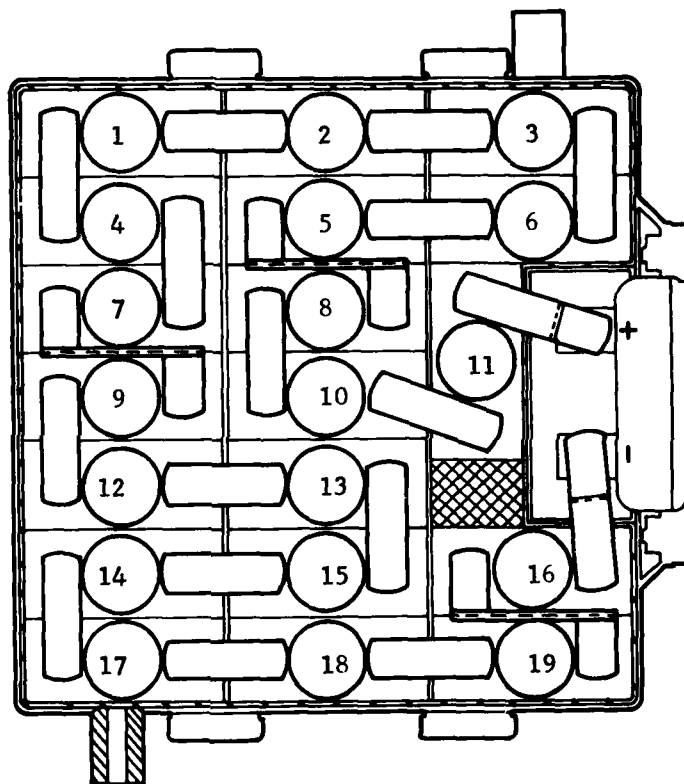
Figure A-1. Battery cell location diagram.

TABLE A-2. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 1A (1st RUN) - 28.4V

Cell No.	Water Usage (cc)		
	Cycle 144	Cycle 287	Cycle 430
1	-4.5	0	0
2	-3.8	0	0
3	-3.8	0	0
4	-3.5	0	0
5	-4.4	0	0
6	-3.2	0	0
7	-3.7	0	0
8	-4.5	1.4	0
9	-3.8	0	1.0
10	-4.7	0	0
11	-5.5	0	0
12	-4.8	0	0
13	-4.9	0	0
14	-4.5	1.4	0
15	-4.6	0	0
16	-3.4	0.4	0.6
17	-4.8	0	0
18	-4.3	0	0.6
19	-4.5	0	0
Subtotals	-81.2	3.2	2.2
Cumulative Totals	-81.2	-78.0	-75.8

Capacity (amp-hr)			
Cycle 0	Cycle 144	Cycle 287	Cycle 430
13.56	12.03	10.45	8.06

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TABLE A-3. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 1B (1st RUN) - 28.4V

Cell No.	Water Usage (cc)		
	Cycle 144	Cycle 287	Cycle 430
1	- 3.5	0	0
2	- 4.2	0	0
3	- 3.4	0	0
4	- 3.5	0	0
5	- 4.0	0	0
6	- 3.0	0	0
7	- 3.0	0	0
8	- 3.5	0	0
9	- 3.8	0	0
10	- 2.5	0	0
11	- 2.8	0	0
12	- 4.8	0	0
13	- 4.6	0	0
14	- 4.0	0	0
15	- 3.2	1.0	0
16	- 3.6	0	0.8
17	- 4.2	0	0
18	- 3.7	0	0
19	- 4.1	0	0
Subtotals	-69.4	1.0	0.8
Cumulative Totals	-69.4	-68.4	-67.6

Capacity	(amp-hr)		
Cycle 0	Cycle 144	Cycle 287	Cycle 430
12.1	11.9	8.8	6.78
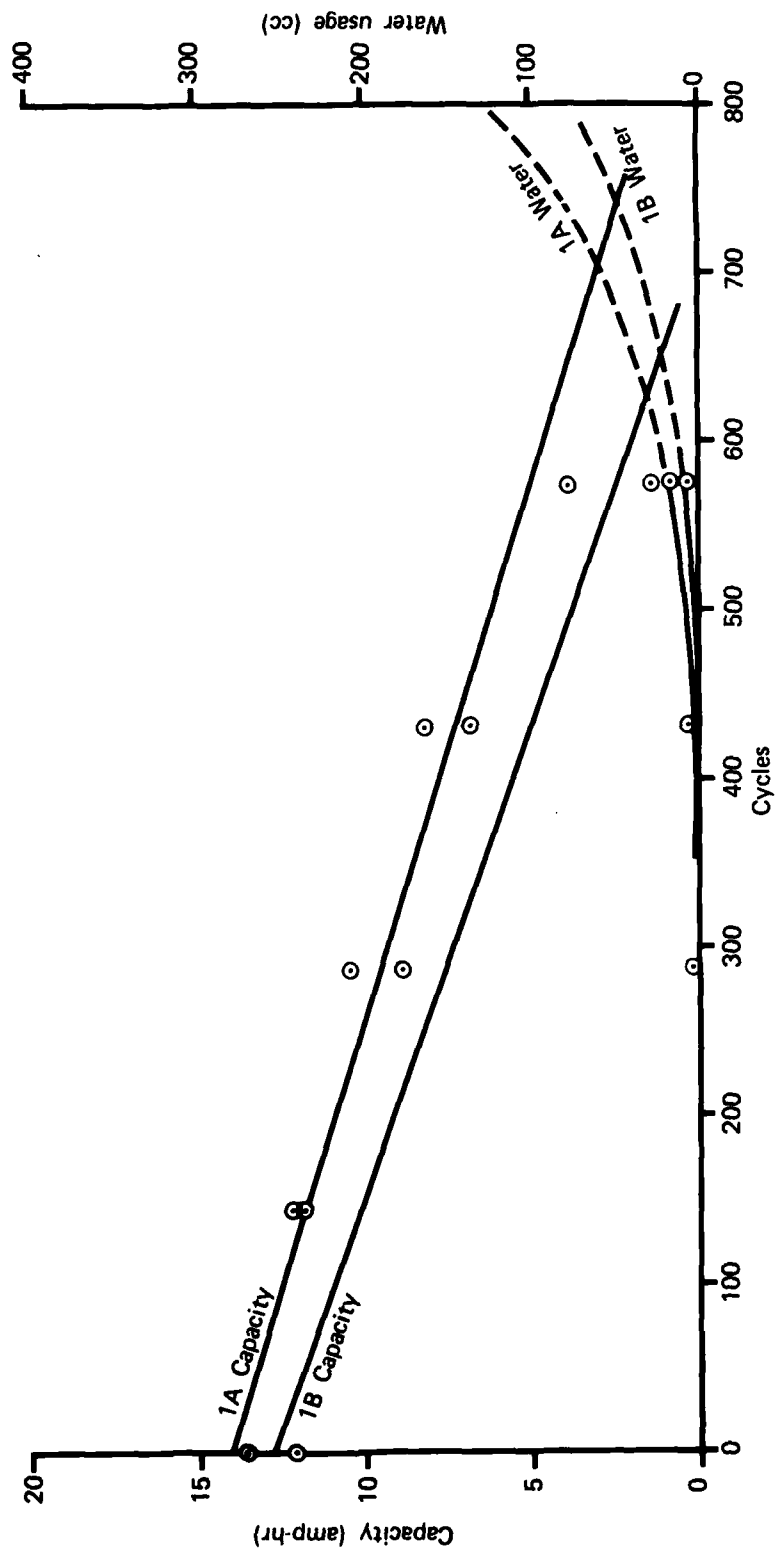
Figure A-2. Capacity/water relationship for constant potential batteries —
20% D-O-D (1st run) — 28.4V.

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TABLE A-4. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 1A (2d RUN) - 29.7V

Cell No.	Water Usage (cc)		
	Cycle 109	Cycle 144	Cycle 200
1	13	2.0	11.0
2	11.4	2.0	8.2
3	9.6	3.0	11.0
4	10.4	1.5	7.6
5	9.0	4.4	13.0
6	12.0	3.0	13.0
7	10.0	2.2	12.4
8	13.0	5.2	11.6
9	13.8	3.6	14.6
10	16.0	2.0	11.4
11	13.6	2.8	13.6
12	11.6	1.6	11.8
13	11.9	3.0	11.4
14	12.0	3.0	12.0
15	10.0	2.4	13.0
16	11.2	1.8	13.0
17	10.0	3.4	11.0
18	13.0	3.0	10.0
19	11.6	2.4	13.6
Subtotals	222.2	52.3	223.2
Cumulative Totals	222.2	274.5	497.7

Capacity (amp-hr)								
Cycle 0	Cycle 109	Cycle 144	Cycle 200	Cycle 235	Cycle 274	Cycle 334	Cycle 372	Cycle 408
13.53	8.25	13.75	11.55	10.45	9.16	8.06	6.96	6.60

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TABLE A-5. WATER USAGE/CAPACITY - 20% D-O-D, BATTERY 1B (2d RUN) - 29.7V

Water Usage (cc)

Cell No.	Cycle 109	Cycle 144	Cycle 200
1	9.2	1.0	10.0
2	8.4	1.0	7.6
3	5.4	1.4	6.0
4	4.4	3.6	9.6
5	2.4	3.0	9.0
6	3.0	3.0	8.0
7	9.0	2.0	8.0
8	5.0	3.0	8.0
9	3.0	2.8	10.0
10	6.0	2.8	8.2
11	9.0	4.2	8.6
12	3.0	0	7.6
13	3.2	2.0	9.4
14	3.8	2.4	9.0
15	6.0	0.8	8.8
16	9.6	1.6	4.0
17	7.4	1.4	4.0
18	8.0	1.4	4.4
19	9.0	0	7.0
Subtotals	114.8	37.4	147.2
Cumulative Totals	114.8	152.2	299.4

Capacity (amp-hr)

Cycle 0	Cycle 109	Cycle 144	Cycle 200	Cycle 235	Cycle 274	Cycle 334	Cycle 372	Cycle 408
13.49	10.2	11.18	9.16	6.41	5.50	4.76	4.03	4.19
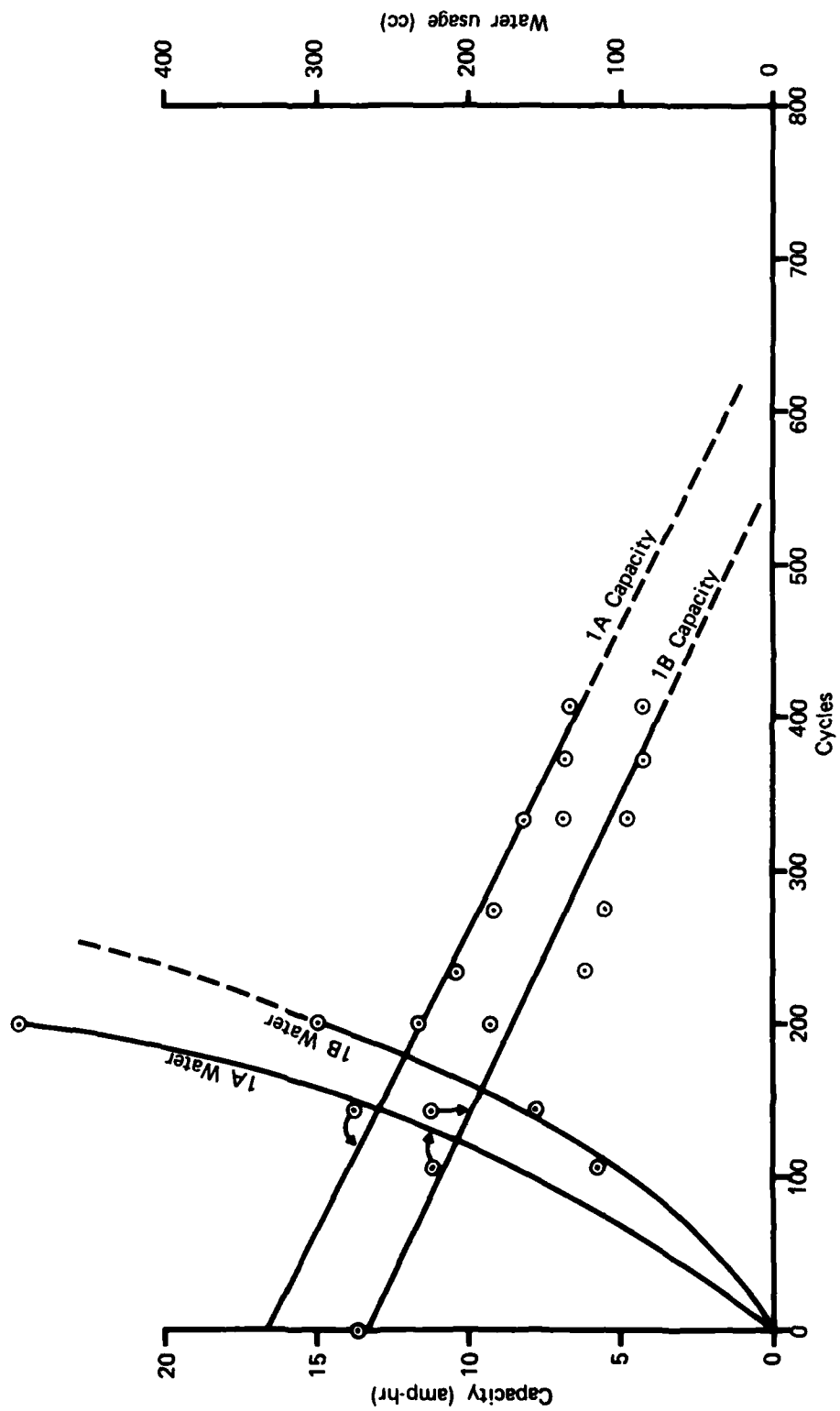
Figure A-3. Capacity/water relationship for constant potential batteries --
20% D-O-D (2d run) — 29.4V.

TABLE A-6. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 2A

Water Usage (cc)

Cell No.	Cycle 46	Cycle 119	Cycle 174	Cycle 251	Cycle 392	Cycle 532
1	0	2.85	1.1	5.0	11.6	15.6
2	1.0	0.75	0.8	2.9	10.1	9.4
3	0	1.10	2.6	4.0	3.5	13.4
4	0.05	1.60	3.2	2.3	11.5	11.0
5	0	0.50	3.3	1.9	8.5	9.8
6	- 3.0	0.40	0.8	2.8	9.7	11.0
7	0	1.75	1.6	1.5	5.6	11.8
8	0	2.00	0.9	2.8	8.5	14.4
9	0	2.30	0.8	6.7	3.7	11.6
10	0	0.30	0.6	2.6	5.9	12.6
11	0.4	1.20	1.4	1.6	14.1	14.6
12	0	2.80	0.7	0.8	6.2	14.0
13	-1.0	0.65	0.6	1.6	11.3	16.2
14	-0.3	0.85	2.7	3.2	9.5	6.6
15	-1.0	0.35	1.1	2.3	10.0	6.2
16	0	1.50	1.2	1.6	10.9	11.6
17	0	1.35	0.8	2.5	9.7	12.4
18	- 2.0	0	1.1	1.7	1.2	6.6
19	-0.8	1.35	2.2	2.8	8.2	9.2
Subtotals	-6.65	23.6	27.5	50.6	159.7	218.0
Cumulative Totals	-6.65	17.0	44.0	95.0	255.0	473.0

Capacity (amp-hr)

Cycle 0	Cycle 46	Cycle 119	Cycle 174	Cycle 251	Cycle 392	Cycle 532
14.21	14.05	13.27	12.79	12.43	11.74	11.27

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TABLE A-7. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 2B

	Water Usage (cc)					
Cell No.	Cycle 46	Cycle 119	Cycle 174	Cycle 251	Cycle 392	Cycle 532
1	0	0.8	2.2	2.2	9.0	7.0
2	0.1	2.0	3.4	4.6	14.0	4.2
3	0.5	1.1	5.2	3.1	4.0	14.4
4	0	0.5	2.8	4.7	6.2	16.4
5	0	0.5	0.8	1.6	11.0	10.8
6	0.4	2.5	1.4	1.9	13.4	3.0
7	0	0.75	1.6	2.7	1.6	3.6
8	0	0	1.5	4.0	14.0	3.2
9	0.2	2.05	2.0	4.9	3.6	13.4
10	0.4	1.6	2.3	4.9	13.4	3.0
11	0	0.8	1.0	5.2	9.0	3.8
12	0	0.7	1.6	2.0	9.4	4.0
13	0.2	1.4	2.9	2.6	8.4	10.4
14	0.6	0.8	2.1	1.3	14.4	1.4
15	0.4	0.9	1.5	3.4	17.6	1.6
16	0	0.8	2.1	1.9	11.0	6.6
17	0	3.4	1.5	1.8	14.0	5.4
18	-0.2	0.7	1.8	2.5	10.2	3.0
19	0	1.2	3.8	4.6	10.8	3.4
Subtotals	2.6	22.5	41.5	59.9	195.0	208.0
Cumulative Totals	2.6	25.1	66.6	126.5	321.0	530.0

	Capacity (amp-hr)						
Cycle 0	Cycle 46	Cycle 119	Cycle 174	Cycle 251	Cycle 392	Cycle 532
14.08	14.05	13.56	12.88	12.73	11.96	12.18
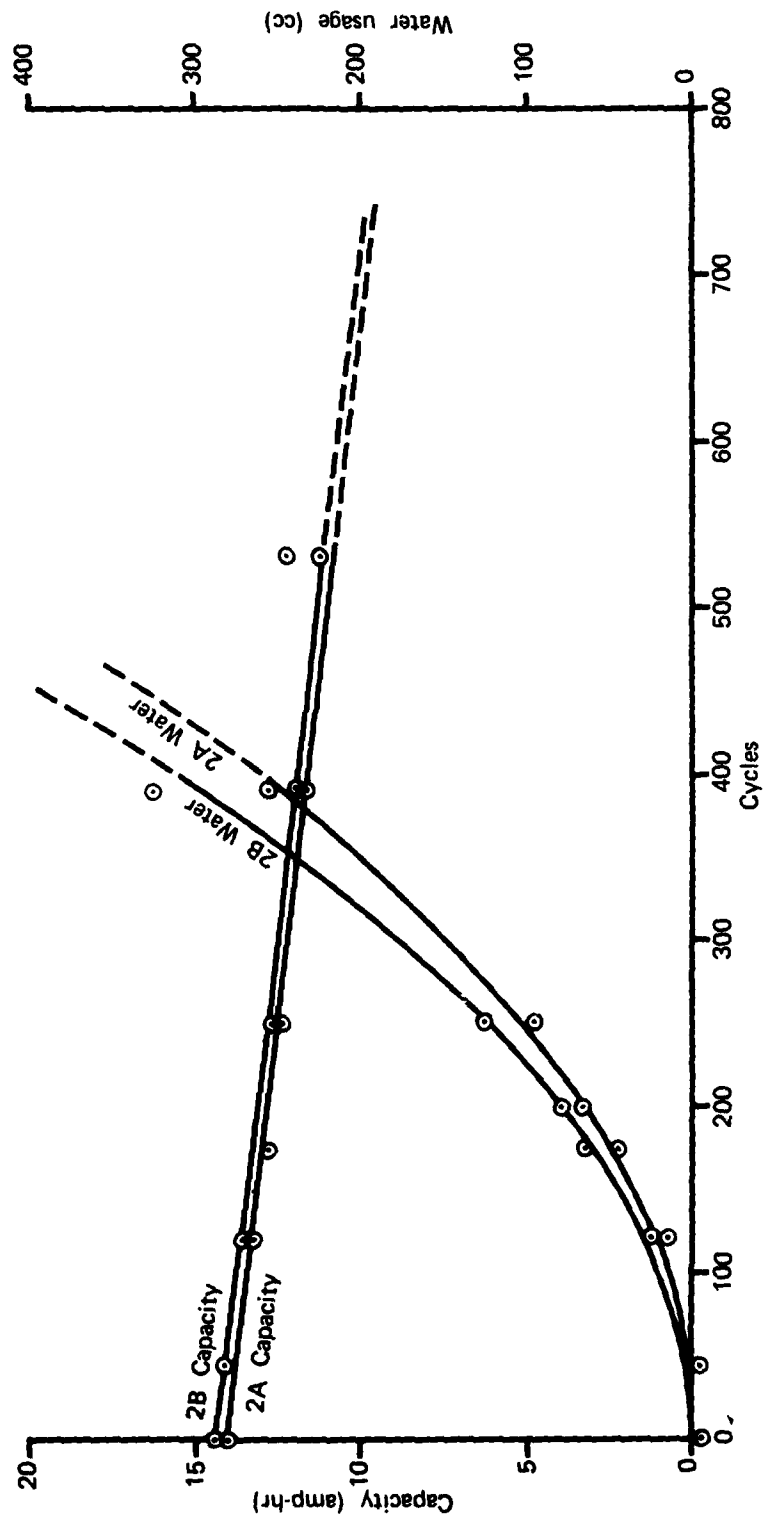
Figure A-4. Capacity/water relationship for Chrysler charger batteries --
20% D-O-D.

TABLE A-8. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 3A

Cell No.	Water Usage (cc)			
	Cycle 140	Cycle 280	Cycle 420	Cycle 560
1	3.0	14.8	11.0	5.6
2	0.8	16.2	12.2	3.4
3	1.6	11.4	13.6	10.6
4	1.8	13.0	13.4	8.2
5	1.6	12.6	13.0	9.4
6	2.4	14.0	14.0	12.2
7	1.4	10.4	14.0	10.0
8	1.4	11.6	15.4	8.6
9	2.0	11.2	11.6	10.0
10	3.8	12.8	12.0	7.6
11	5.4	10.2	15.0	6.2
12	2.8	13.4	15.0	8.2
13	3.6	15.2	15.0	10.0
14	2.0	13.8	10.6	13.4
15	3.0	15.6	10.4	14.8
16	6.4	15.4	10.8	10.2
17	6.4	13.2	12.8	5.6
18	5.2	9.6	11.6	4.4
19	2.0	10.0	12.0	4.4
Subtotals	56.6	244.4	243.0	163.0
Cumulative Totals	56.6	301.0	544.0	707.0

Capacity (amp-hr)				
Cycle 0	Cycle 140	Cycle 280	Cycle 420	Cycle 560
12.04	13.68	12.71	10.99	9.62

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TABLE A-9. WATER USAGE/CAPACITY - 20% D-O-D, BATTERY 3B

Cell No.	Water Usage (cc)			
	Cycle 140	Cycle 280	Cycle 420	Cycle 560
1	4.2	3.0	15.0	6.0
2	3.6	14.0	12.0	5.0
3	0.8	12.0	11.8	4.0
4	1.4	10.6	13.2	11.2
5	1.6	13.6	11.0	6.0
6	1.8	14.0	13.2	7.8
7	1.8	9.8	11.6	13.2
8	1.8	10.0	14.4	11.6
9	1.8	10.6	13.0	11.4
10	2.0	13.0	10.6	10.0
11	0	13.0	11.0	9.8
12	2.4	12.0	14.0	5.8
13	3.2	14.4	10.4	9.2
14	1.4	10.6	14.2	11.8
15	2.0	3.6	19.0	4.6
16	2.2	12.8	13.0	5.0
17	4.8	8.6	13.2	4.0
18	2.2	9.6	18.8	8.2
19	1.8	13.4	13.0	10.6
Subtotals	40.8	208.6	252.4	170.2
Cumulative Totals	40.8	249.4	501.8	672.0

Capacity (amp-hr)				
Cycle 0	Cycle 140	Cycle 280	Cycle 420	Cycle 560
13.27	13.41	11.70	11.33	11.0
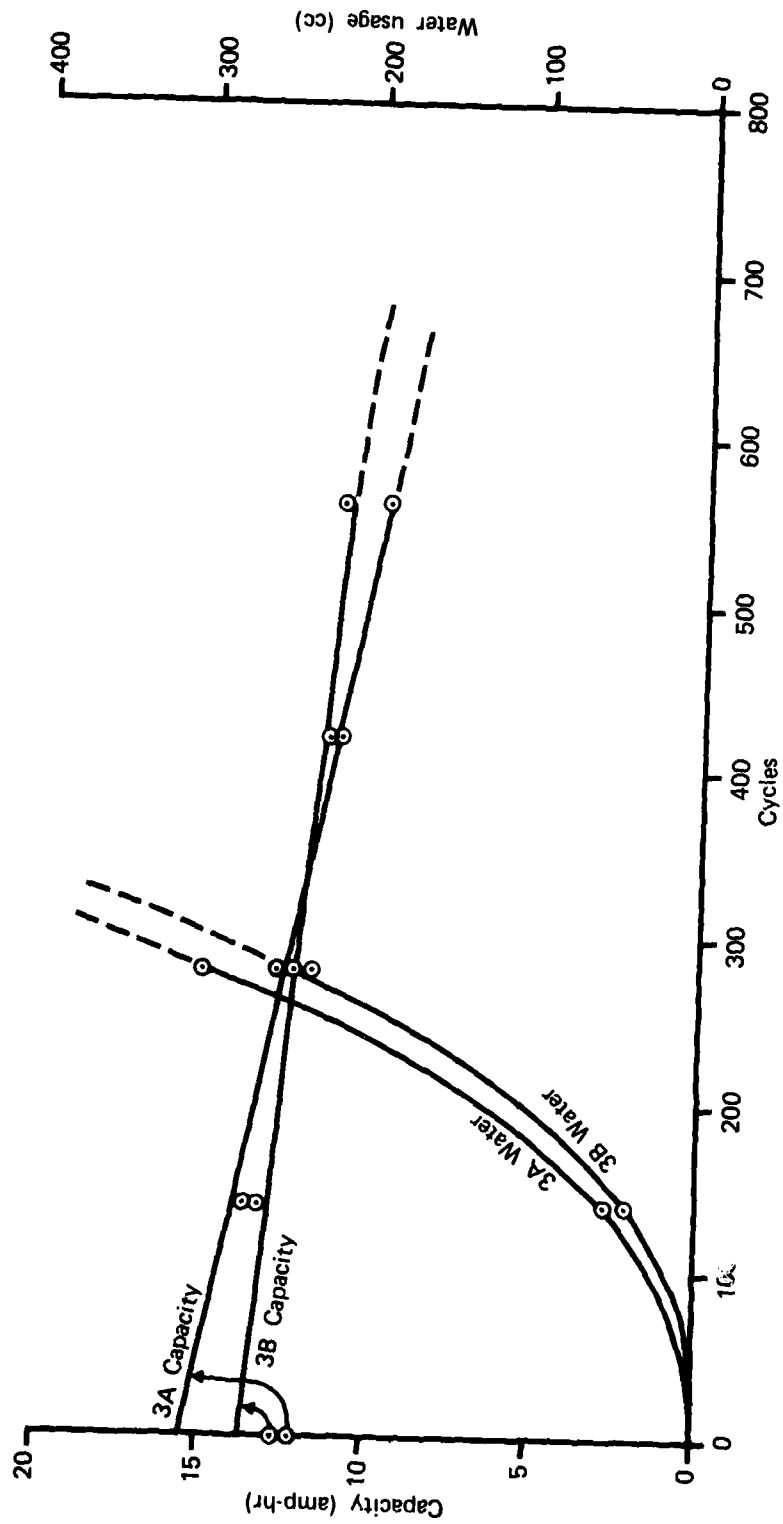
Figure A-5. Capacity/water relationship for Utah R&D charger batteries — 20% D-O-D.

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TABLE A-10. WATER USAGE/CAPACITY - 20% D-O-D, BATTERY 4A

	Water Usage (cc)		
Cell No.	Cycle 144	Cycle 287	Cycle 416
1	-4.7	-1.3	5.0
2	-4.4	-1.0	3.4
3	-0.8	-1.0	4.0
4	-0.8	-1.0	5.4
5	-2.4	0	3.0
6	-3.4	0.4	3.2
7	0	0	4.2
8	0	0.6	4.6
9	-1.9	-1.0	3.4
10	-3.7	0	4.0
11	-3.0	0	4.4
12	-1.7	0	3.6
13	0	0	5.0
14	-2.0	0	4.4
15	0	0	4.6
16	-0.4	-1.0	3.2
17	-2.1	0	3.2
18	0	0	4.4
19	-2.2	0	2.4
Subtotals	-33.4	-5.3	75.4
Cumulative Totals	-33.4	-38.7	36.7

Capacity (amp-hr)			
Cycle 0	Cycle 144	Cycle 287	Cycle 416
13.08	10.63	6.78	—

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TABLE A-11. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 4B

	Water Usage (cc)		
Cell No.	Cycle 144	Cycle 287	Cycle 416
1	-2.1	0.6	3.4
2	-2.0	-1.7	4.0
3	-2.1	0	2.2
4	-2.8	0	4.0
5	-3.6	0	1.0
6	0	0	6.4
7	-1.1	0	4.2
8	-4.3	0	2.4
9	-2.8	0	3.0
10	-2.7	0	1.6
11	-2.5	0	3.0
12	-1.3	0	1.4
13	-4.0	0	3.0
14	-3.6	0	3.6
15	0	0	4.2
16	-3.3	0	2.2
17	-3.0	0	2.4
18	-1.8	0	4.2
19	-3.3	0	4.4
Subtotals	-46.3	-1.1	60.6
Cumulative Totals	-46.3	-47.4	13.2

	Capacity	(amp-hr)	
Cycle 0	Cycle 144	Cycle 287	Cycle 416
12.18	11.0	8.43	—

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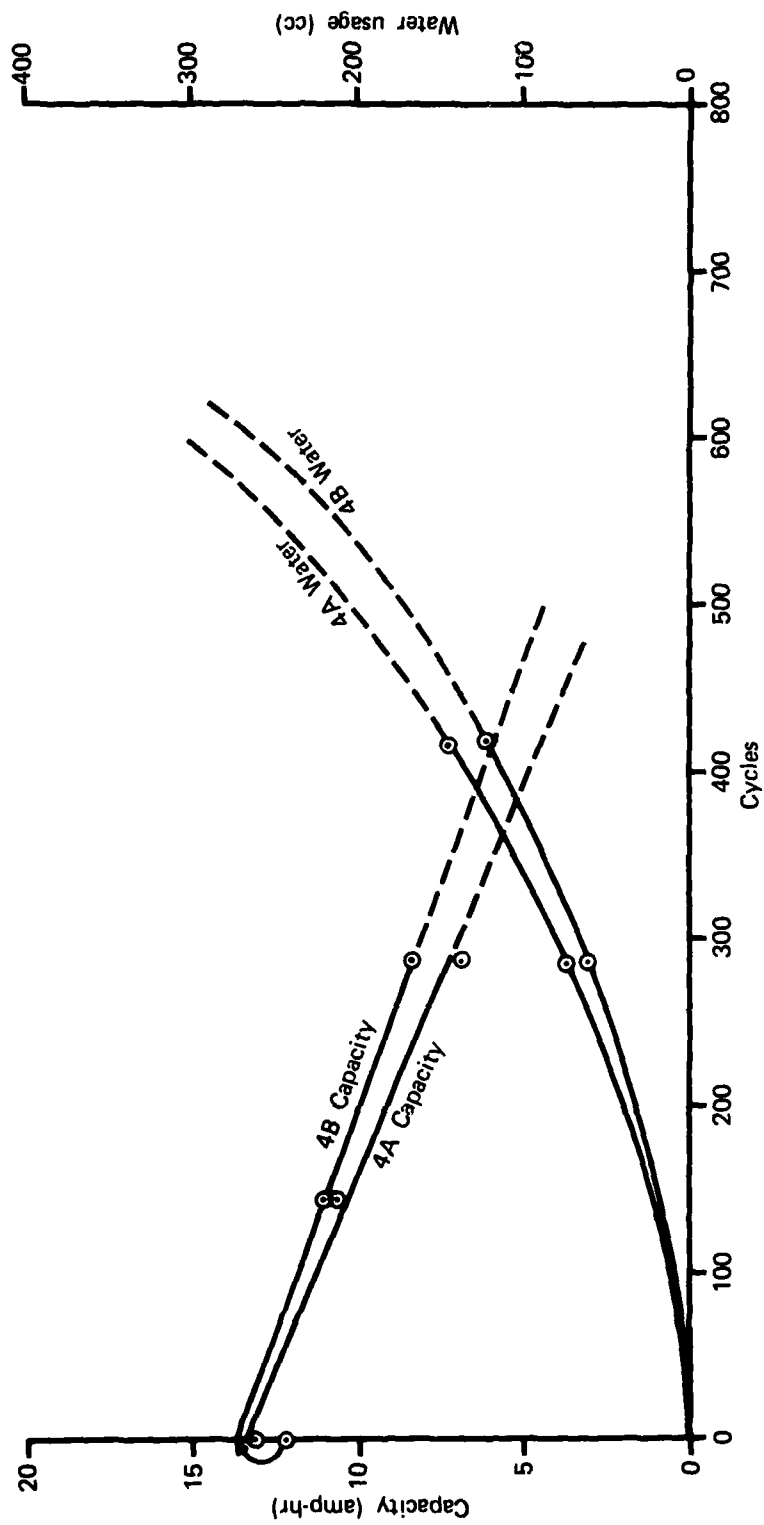
Figure A-6. Capacity/water relationship for Aerospace charger batteries –
20% D-O-D.

TABLE A-12. WATER USAGE/CAPACITY - 20% D-O-D, BATTERY 5A

	Water Usage (cc)			
Cell No.	Cycle 140	Cycle 283	Cycle 427	Cycle 550
1	-3.9	2.0	17.0	6.6
2	-2.3	3.0	15.2	8.2
3	-3.0	3.0	17.0	10.6
4	-0.8	2.4	16.0	10.6
5	-4.0	3.4	19.0	13.8
6	-2.0	4.0	14.0	7.4
7	-3.4	3.0	14.0	11.4
8	0	3.0	17.0	12.6
9	-2.0	3.6	15.6	10.4
10	-4.5	2.8	14.0	9.6
11	-2.7	4.0	14.0	11.8
12	-2.7	3.0	17.0	11.0
13	0	3.0	17.4	12.4
14	-3.5	3.4	16.0	10.0
15	-4.5	3.6	20.0	9.4
16	-4.6	4.0	18.2	9.8
17	-2.7	3.2	17.0	9.4
18	-5.2	3.2	19.6	10.2
19	-3.0	2.6	18.0	5.0
Subtotals	-54.8	60.2	316.0	190.2
Cumulative Totals	-54.8	5.4	321.4	511.6

Capacity (amp-hr)					
Cycle 0	Cycle 140	Cycle 283	Cycle 427	Cycle 550	Cycle 692
12.43	13.38	13.38	11.36	13.01	11.73

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TABLE A-13. WATER USAGE/CAPACITY - 20% D-O-D,
BATTERY 5B

	Water Usage (cc)			
Cell No.	Cycle 140	Cycle 283	Cycle 427	Cycle 550
1	0	3.6	15.4	11.0
2	0	4.4	16.4	11.6
3	0	5	18.4	5.4
4	0	2	17.2	5.4
5	0	6.6	19.6	2.4
6	-2.1	2.8	21.0	4.0
7	0	2.0	18.6	3.6
8	0	1.6	18.2	2.4
9	0	2.0	19.0	4.8
10	0	3.0	16.6	6.4
11	0	2.6	20.4	6.6
12	0	3.4	16.0	8.0
13	0.6	5.6	20.4	12.4
14	0	3.4	18.4	7.0
15	-1.3	2.0	23.4	3.0
16	0	3.4	22.4	3.6
17	-2.5	4.2	20.4	5.6
18	0	4.8	19.6	10.8
19	1.0	4.6	20.0	8.8
Subtotals	-4.3	67.0	361.4	122.8
Cumulative Totals	-4.3	62.7	424.1	546.9

Capacity (amp-hr)					
Cycle 0	Cycle 140	Cycle 283	Cycle 427	Cycle 550	Cycle 692
12.5	13.93	13.75	11.0	13.38	11.37

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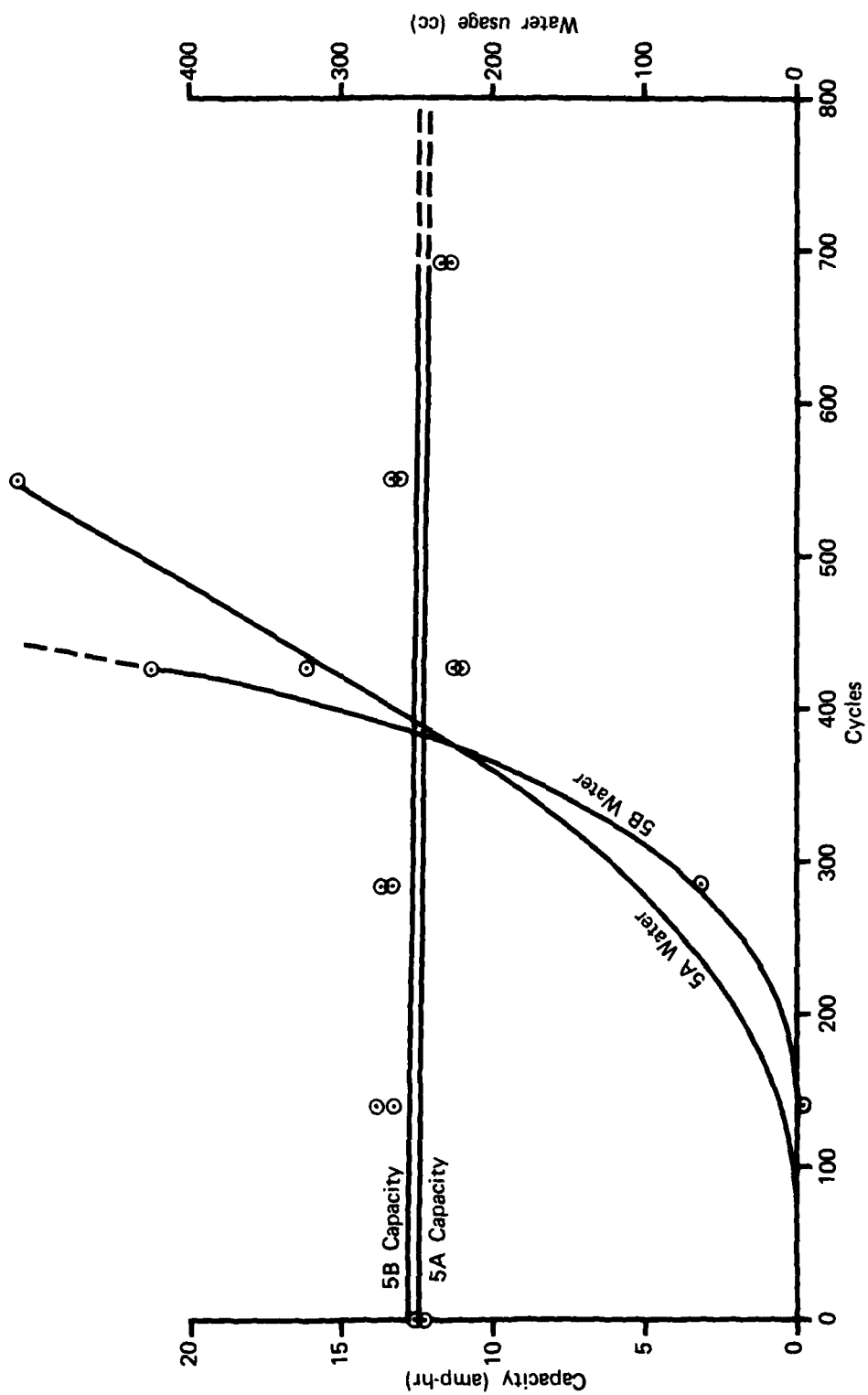
Figure A-7. Capacity/water relationship for Eldec charger batteries — 20% D-O-D.

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TABLE A-14. CAPACITY VERSUS DEEP-CYCLE RECONDITIONING —
20% D-O-D, BATTERIES 6A, 6B, 2A, 2B

| | | Capacity (amp-hr) | | | |
| | | Constant Potential | | Chrysler | |
	Cycles	Battery 6A	Battery 6B	Battery 2A	Battery 2B
First Run	0	13.63	13.35	14.21	14.08
	46	12.51	12.28	14.05	14.05
	119	11.11	10.69	13.27	13.56
	174	10.39	8.80	12.79	12.89
	259	9.25	7.10	12.43	12.73
	392	*	*	11.74	11.96
	532	*	*	11.27	12.18
	672	*	*	10.97	11.58
Second Run	0	11.07	10.49	12.10	12.28
	140	8.89	7.67	10.27	7.80
	280	4.50	3.72	4.22	1.84
	358	2.90	2.16	–	–
Third Run	0	12.10	12.98	**	11.40
	120	5.48	6.60	**	7.15
	221	1.82	2.25	**	–
	248	–	–	**	1.46

— No reading taken
* Power supply failed
** Charger 2A failed

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TABLE A-15. CAPACITY VERSUS DEEP-CYCLE RECONDITIONING —
20% D-O-D, BATTERIES 1A, 1B, 5A, 5B

	Capacity (amp-hr)			
	Constant Potential (2d run at 29.7V)		Eldec (2d run)	
Cycles	Battery 1A	Battery 1B	Battery 5A	Battery 5B
0	13.20	11.18	14.60	13.00
57	10.81	—	—	—
77	—	—	14.12	11.73
84	—	4.76	—	—
120	5.86	—	—	—
135	—	—	12.83	11.18
215	—	—	10.81	9.71
273	—	—	10.08	7.88
331	—	—	7.88	5.68

— No reading taken

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APPENDIX B
50% DEPTH-OF-DISCHARGE TEST DATA

The 50% D-O-D test was too severe to collect meaningful capacity/water usage performance data. Capacity falloff was almost immediate, diminishing to less than 5 amp-hr in one week. The data that was collected is presented here for information only.

The test was conducted in accordance with Table B-1.

TABLE B-1. 50% D-O-D PROFILE*

Function	Amps	Time	Volts
Discharge	11	30 minutes	Not less than 19V
Charge	Charger profile	1.5 hours	Charger profile
Rest	0	1 hour	Battery voltage

$$*50\% \text{ of rated capacity} = \frac{11 \text{ amps} \times 30 \text{ min}}{60} = 5.5 \text{ amp-hr}$$

This cycle test was to be continued until sufficient cycles had been accumulated to accurately define the chargers' performance characteristics; however, this was not possible due to rapid capacity falloff. The following graphs (Figures B-1 through B-5) show the data that was collected. A brief description of the events leading up to data collection for each graph is provided in the following paragraphs. Tables B-2 through B-11 show test data in tabular form.

CONSTANT POTENTIAL CHARGE

The 50% D-O-D run was conducted using batteries 6A and 6B. Prior to starting the 50% D-O-D run, these batteries had been cycled at the 20% D-O-D level, and therefore were not new (never used) batteries. The batteries had been received in new condition. After being made ready for service, the batteries were cycled at the 20% D-O-D level for 251 cycles. Following this run, the batteries were deep-cycled and run again at the 20% D-O-D level. This run continued until battery 6A had accrued 466 cycles and battery 6B had accrued 358 cycles. After this run, the batteries were deep-cycled and the 50% D-O-D run was accomplished. The data collected for the 50% D-O-D run is presented in Figure B-1.

CHRYSLER CHARGERS

The 50% D-O-D run was conducted on batteries 2A and 2B. This run was accomplished after these batteries had been cycled at the 20% D-O-D level for 672 cycles.

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The batteries were deep-cycled prior to the start of the 50% D-O-D run. Data collected is shown in Figure B-2.

UTAH R&D CHARGERS

The 50% D-O-D run was conducted on batteries 3A and 3B. The run was accomplished after these batteries had been cycled at the 20% D-O-D level for 560 cycles. The batteries were deep-cycled prior to the start of the 50% D-O-D run. Data collected is shown in Figure B-3.

AEROSPACE AVIONICS CHARGERS

The 50% D-O-D run was conducted on batteries 7A and 7B. This run was accomplished after these batteries had been cycled at a 16% D-O-D level for 700 cycles. The batteries were deep-cycled prior to the start of the 50% D-O-D run. Data collected is shown in Figure B-4. Charger 7B experienced a failure after 20 cycles and was removed from the test. The failure resulted in a constant 9 amps being forced into the battery instead of the normal pulsing current profile. This constant 9 amp overcharge is evidenced by the high water usage and high capacity recordings on battery 7B.

ELDEC CHARGERS

The 50% D-O-D run was conducted on batteries 8A and 8B. They were received as new batteries, made ready for service, and entered the test at the 50% D-O-D level. This test was continued for 108 cycles. Data collected is shown in Figure B-5.

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TABLE B-2. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 6A		TABLE B-3. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 6B	

TABLE B-2. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 6A

	Water Usage (cc)
Cell No.	Cycle 54
1	3.4
2	2.6
3	2.0
4	2.2
5	2.4
6	2.0
7	2.6
8	2.8
9	2.0
10	2.8
11	2.0
12	2.0
13	2.0
14	2.6
15	2.6
16	2.6
17	2.4
18	2.4
19	2.4
Subtotals	45.8
Cumulative Totals	45.8

Capacity (amp-hr)	
Cycle 0	Cycle 54
13.56	2.33

TABLE B-3. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 6B

	Water Usage (cc)
Cell No.	Cycle 54
1	2.0
2	2.0
3	2.0
4	2.0
5	2.0
6	2.0
7	2.0
8	2.0
9	2.0
10	2.0
11	2.0
12	2.0
13	2.0
14	2.0
15	2.0
16	2.0
17	2.0
18	2.4
19	2.0
Subtotals	38.4
Cumulative Totals	38.4

Capacity (amp-hr)	
Cycle 0	Cycle 54
13.66	2.37
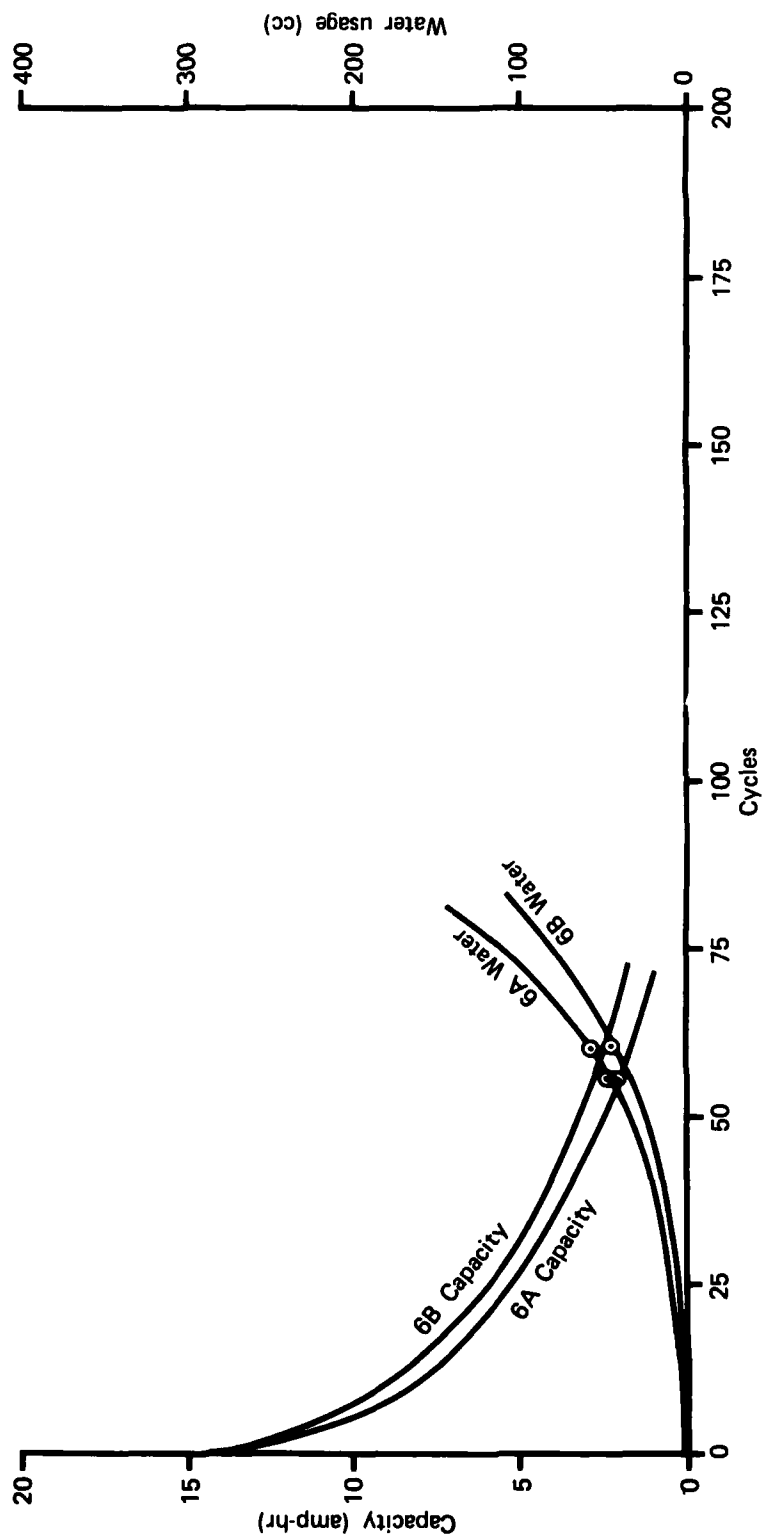
Figure B-1. Capacity/water relationship for constant potential batteries — 50% D-O-D.

TABLE B-4. WATER USAGE/CAPACITY - 50% D-O-D,
BATTERY 2A

Cell No.	Water Usage (cc)		
	Cycle 54	Cycle 68	Cycle 98
1	3.0	2.6	3.0
2	2.0	2.6	2.0
3	3.6	4.4	2.2
4	2.0	2.0	2.0
5	2.0	2.0	2.0
6	2.0	2.0	2.0
7	2.4	2.6	2.2
8	2.0	2.0	2.6
9	2.8	2.8	2.0
10	2.0	2.0	2.0
11	2.0	2.0	2.6
12	2.0	2.8	2.0
13	3.0	2.8	2.4
14	2.0	2.0	2.8
15	2.0	2.6	2.8
16	2.0	2.0	2.0
17	2.0	2.0	2.0
18	3.4	2.8	2.8
19	2.6	3.0	2.2
Subtotals	44.8	46.0	43.6
Cumulative Totals	44.8	90.8	134.4

Capacity (amp-hr)			
Cycle 0	Cycle 54	Cycle 68	Cycle 98
15.36	4.08	4.04	3.62

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TABLE B-5. WATER USAGE/CAPACITY - 50% D-O-D,
BATTERY 2B

	Water Usage (cc)		
Cell No.	Cycle 54	Cycle 68	Cycle 82
1	3.6	3.4	3.0
2	2.0	2.0	2.0
3	3.6	3.0	2.4
4	2.6	2.6	2.6
5	2.0	2.4	2.8
6	1.5	2.0	2.0
7	2.0	2.0	2.0
8	2.0	2.0	2.0
9	0.8	1.4	2.0
10	3.4	2.6	3.2
11	5.4	2.6	2.0
12	2.0	2.4	2.0
13	4.2	3.2	3.2
14	2.0	2.0	2.0
15	3.6	3.2	2.0
16	0.7	1.6	2.0
17	4.2	2.8	3.2
18	2.0	2.0	2.0
19	-1.2	1.8	1.8
Subtotals	46.4	45.0	44.2
Cumulative Totals	46.4	91.4	135.6

Capacity (amp-hr)			
Cycle 0	Cycle 54	Cycle 68	Cycle 82
13.93	4.10	3.89	3.59
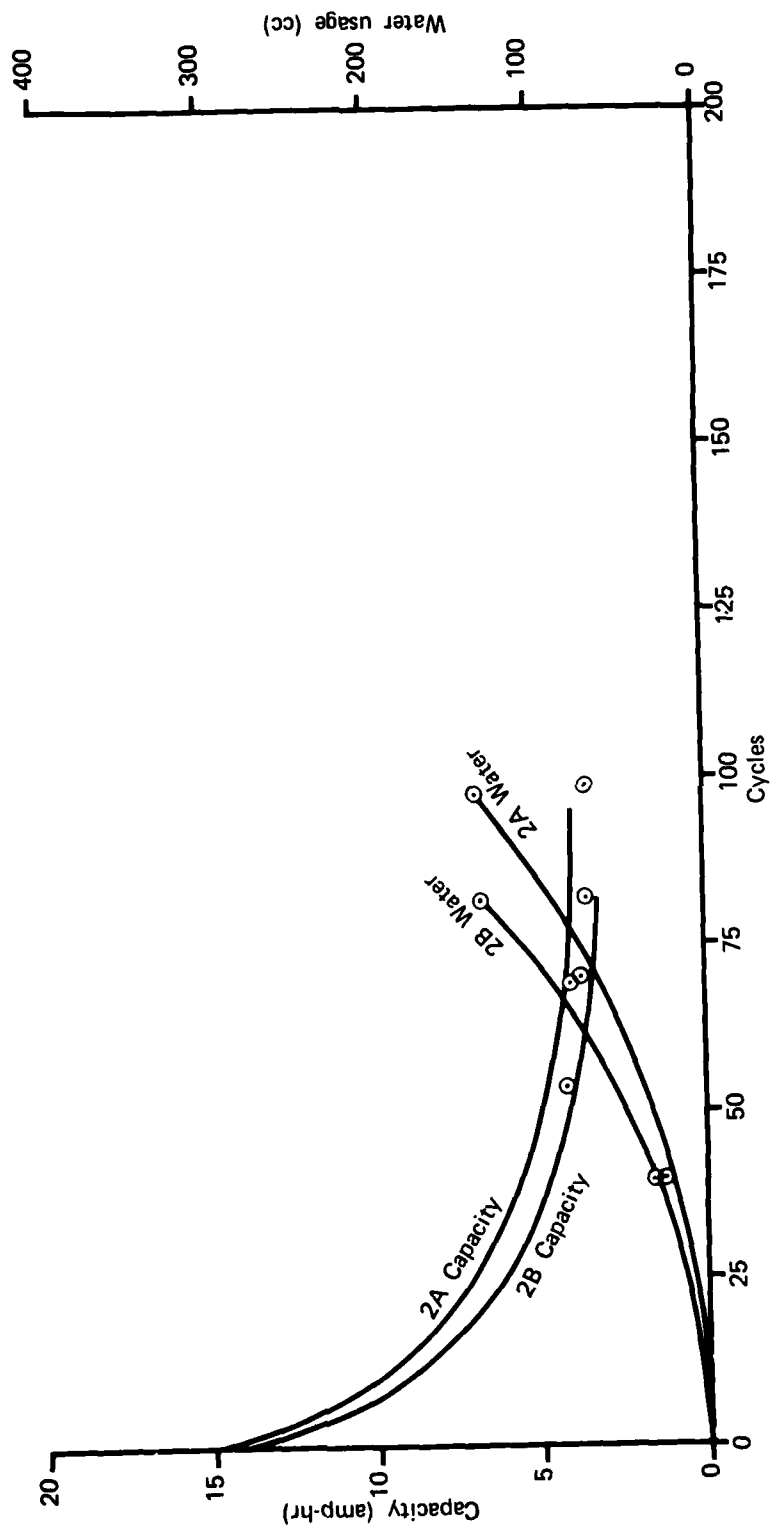
Figure B-2. Capacity/water relationship for Chrysler batteries — 50% D-O-D.

TABLE B-6. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 3A				TABLE B-7. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 3B		

	Water Usage (cc)				Water Usage (cc)	
Cell No.	Cycle 54	Cycle 100		Cell No.	Cycle 54	Cycle 100
1	7.0	6.0		1	2.0	7.0
2	6.0	7.0		2	4.0	5.6
3	6.0	8.0		3	4.0	4.0
4	6.0	6.0		4	5.0	7.6
5	6.0	6.2		5	3.0	6.8
6	6.0	8.2		6	4.0	6.8
7	6.0	6.8		7	3.5	5.6
8	6.0	9.4		8	3.5	8.0
9	6.0	6.0		9	5.0	4.8
10	7.0	8.8		10	5.0	3.6
11	7.0	7.2		11	4.0	5.6
12	6.0	7.8		12	8.0	4.8
13	6.0	8.2		13	3.0	5.8
14	6.0	9.2		14	4.0	5.8
15	6.0	7.0		15	4.0	5.8
16	7.0	7.0		16	3.0	6.0
17	7.0	5.6		17	4.0	5.0
18	6.0	6.8		18	6.0	6.4
19	6.0	11.4		19	3.0	7.6
Subtotals	119.0	142.6		Subtotals	78.0	112.6
Cumulative Totals	119.0	261.6		Cumulative Totals	78.0	190.6

Capacity (amp-hr)				Capacity (amp-hr)		
Cycle 0	Cycle 54	Cycle 100		Cycle 0	Cycle 54	Cycle 100
13.03	5.19	4.71		14.11	7.32	4.73
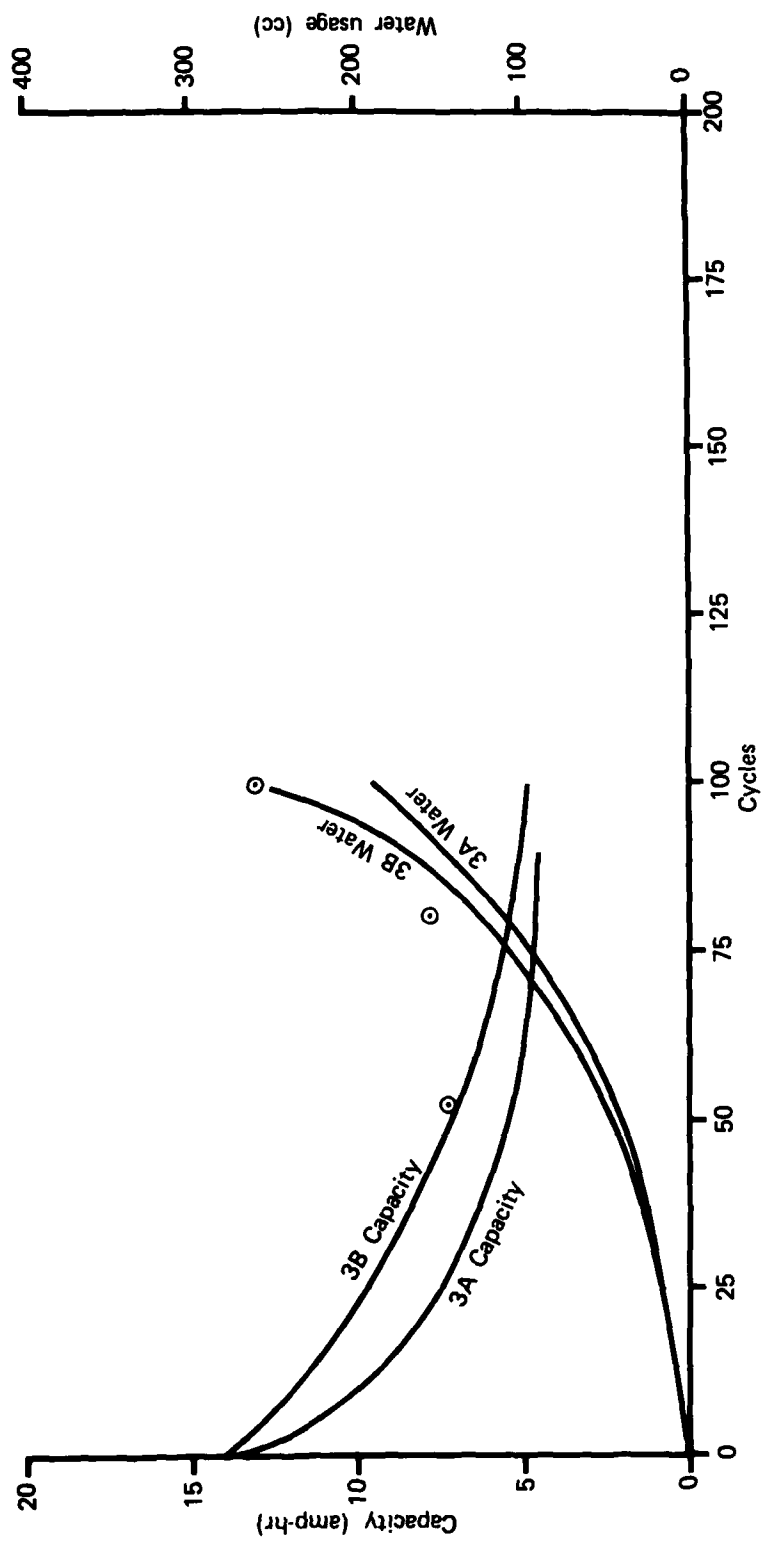
Figure B-3. Capacity/water relationship for Utah R&D batteries — 50% D-O-D.

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TABLE B-8. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 7A			TABLE B-9. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 7B	

Water Usage (cc)			Water Usage (cc)	
Cell No.	Cycle 32		Cell No.	Cycle 24
1	2.5		1	10.0
2	3.0		2	10.9
3	3.0		3	10.8
4	4.0		4	11.2
5	4.0		5	13.3
6	3.0		6	11.7
7	4.0		7	11.3
8	3.0		8	10.6
9	5.0		9	10.0
10	3.0		10	10.3
11	3.0		11	11.6
12	3.0		12	10.5
13	3.0		13	10.8
14	3.0		14	10.4
15	4.0		15	11.8
16	3.0		16	10.3
17	2.0		17	12.2
18	3.0		18	10.9
19	3.0		19	10.6
Subtotals	61.5		Subtotals	209.0
Cumulative Totals	61.5		Cumulative Totals	209.0

Capacity (amp-hr)			Capacity (amp-hr)	
Cycle 0	Cycle 32		Cycle 0	Cycle 24
12.9	2.56		14.72	12.28

NOTE: Charger 7B failed during this test.

Figure B-4. Capacity/water relationship for Aerospace Avionics batteries — 50% D-O-D.
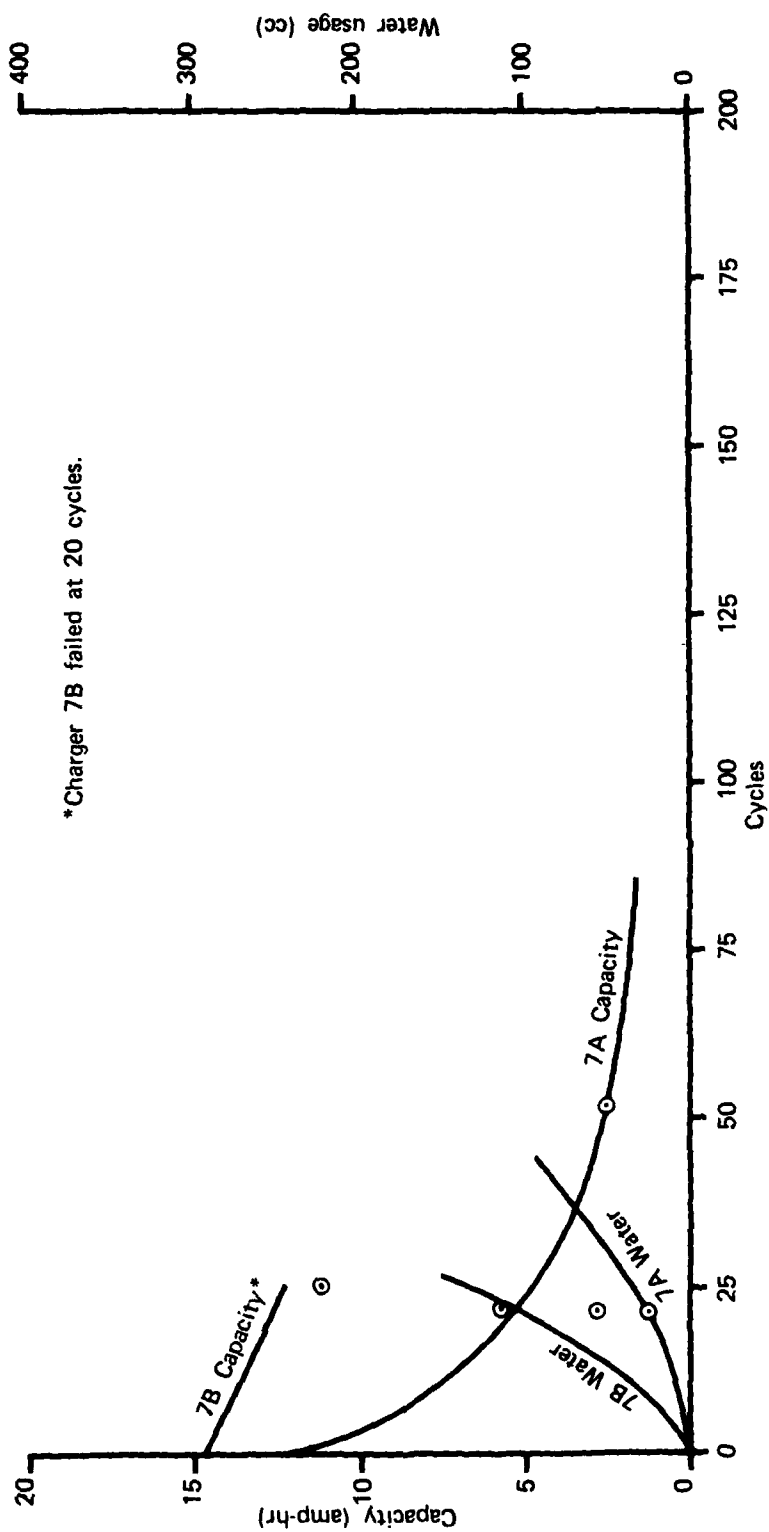
*Charger 7B failed at 20 cycles.

		TABLE B-10. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 8A				TABLE B-11. WATER USAGE/CAPACITY - 50% D-O-D, BATTERY 8B

	Water Usage (cc)			Water Usage (cc)	
Cell No.	Cycle 54	Cycle 108	Cell No.	Cycle 54	Cycle 108
1	0	3.0	1	1.0	4.0
2	0	3.4	2	0	2.0
3	-0.5	3.0	3	0	4.0
4	0	3.2	4	0	3.0
5	-0.2	0	5	0	3.0
6	0	3.0	6	-0.8	2.8
7	0	3.0	7	0	4.0
8	-0.5	1.6	8	0	2.6
9	0	2.2	9	0.8	2.2
10	0	0	10	1.0	5.4
11	0	1.6	10	0	3.4
12	0.6	2.0	11	1.8	5.0
13	0	2.2	13	0	2.2
14	0	1.8	14	0.8	3.8
15	0	0	15	0.6	3.0
16	-1.5	1.8	16	-0.2	2.0
17	-2.4	0	17	1.8	5.0
18	0	1.8	18	0	3.2
19	0	1.8	19	0	4.6
Subtotals	-4.5	35.4	Subtotals	6.8	65.2
Cumulative Totals	-4.5	30.9	Cumulative Totals	6.8	72.0

Capacity (amp-hr)			Capacity (amp-hr)		
Cycle 0	Cycle 54	Cycle 108	Cycle 0	Cycle 54	Cycle 108
14.15	8.9	6.17	13.56	8.9	6.27

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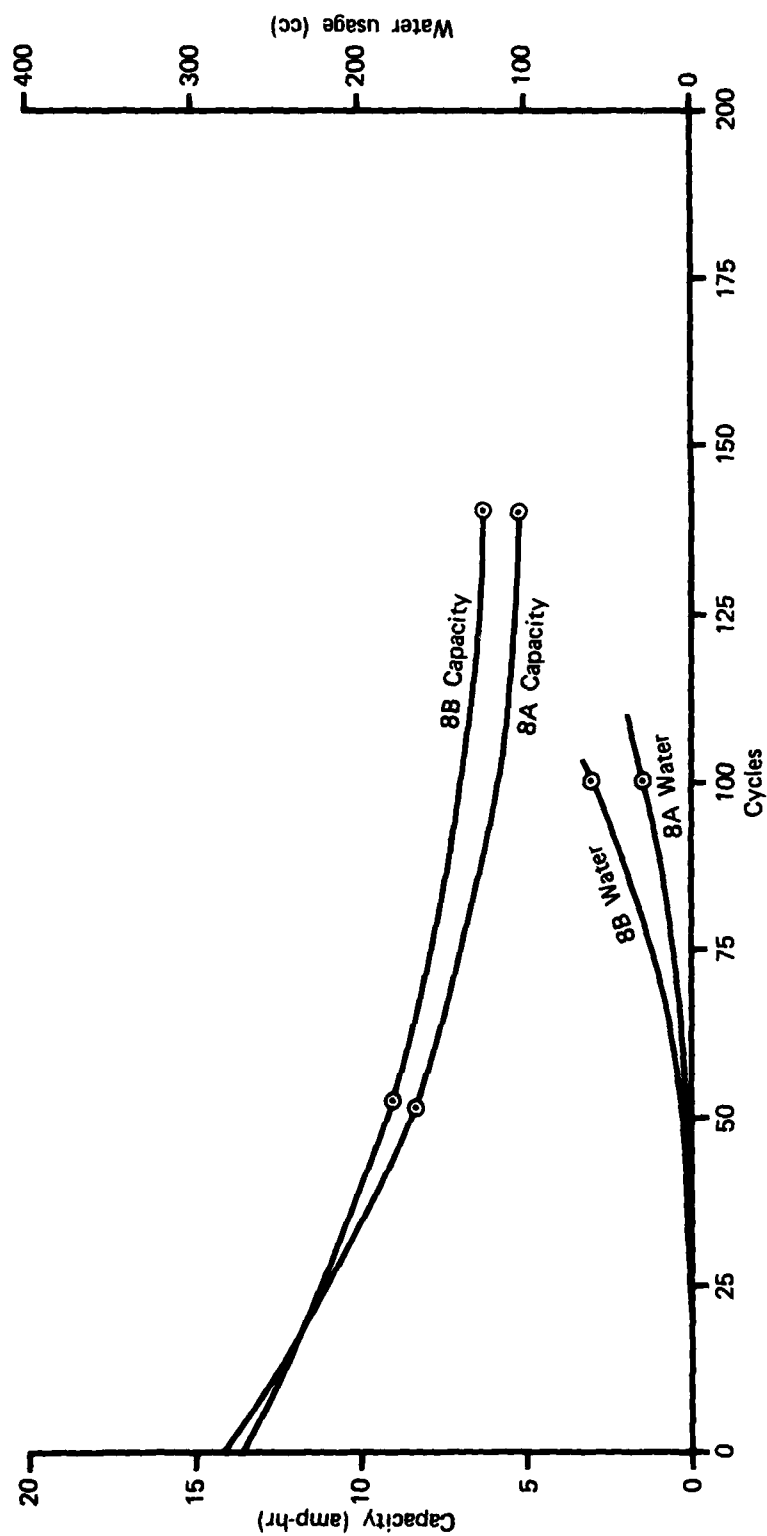
Figure B-5. Capacity/water relationship for Eldec charger batteries — 50% *D-O-D.*

APPENDIX C
BATTERY MAINTENANCE REQUIREMENTS

Significant differences exist in the battery maintenance schedules that are presently recommended by the Army, Navy, Air Force, NASA, and two battery manufacturers. Estimates for improvements in a battery's maintenance schedule that can be expected by using an on-board charger have been established based on a direct comparison to these existing recommended schedules.

Two requirements establish a battery maintenance schedule. First, the battery must be kept in a state of readiness that ensures that adequate starting and standby power is available at all times. If the maintenance schedule does not satisfy this requirement, the battery will not fulfill its intended purpose, and adjustments toward more frequent servicing will be required. Secondly, economic considerations mandate that a maximum time between maintenance actions be established. These two requirements are always at odds with each other; economics trying to lengthen the schedule, and performance trying to shorten it. The optimum trade-off point between these two requirements can not be established if outside influences appreciably affect the battery's performance, as is the case when a NiCad battery is charged from a non-temperature-compensated constant potential charging source such as the aircraft's dc bus. The two major outside influences that affect battery performance when charging on the aircraft's bus are the voltage regulator setting and ambient temperature changes. If the regulator is inadvertently set too low for a particular operating temperature, the battery capacity will rapidly diminish, resulting in a dead battery. If, on the other hand, the regulator is set too high for a particular operating temperature, the electrolyte will rapidly boil off, resulting in battery overheating, fire, explosion, or thermal runaway. Because these conditions directly relate to safety of flight, and because there is no way to eliminate the possibility of their occurrence with the existing bus charge technique, a situation has been created where overservicing is commonplace. If these outside influences could be controlled, thus eliminating the safety implications, the economic requirement to lengthen the schedule could be satisfied. The use of an on-board charger creates just such a situation. By using a temperature-compensated constant-current charge profile, the on-board charger checks these influences, eliminates the safety factors, and permits the establishment of an optimum maintenance schedule.

Every operator who charges the battery directly off the dc bus grapples with these problems. As a result, each operator establishes the schedule that best meets his particular operating mode. Schedules vary greatly between operators. For example:

Army
- Operator checks battery electrolyte level on a weekly or 25-flight-hour basis as required by TM 11-6140-203-14-2.

- Battery is cycled through the battery shop for a deep-cycle reconditioning* on a 120-day or 100-flight-hour basis.

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* Reconditioning refers to deep-cycle discharge to zero volts and recharge followed by a capacity check.

- Carbon pile voltage regulators are adjusted weekly or after 25 flight-hours. Solid-state regulators are adjusted at 120 days or after 100 flight-hours.

Navy
- No operator requirement to check water per NAVAIR 17-15BAD-1 (Reference 3).

- Battery shop capacity check* at 56 days.

- No voltage regulator requirement exists. Some aircraft operators have initiated local requirements.

Air Force
- No operator requirement to check water per TO 8D2-3-1 (Reference 4).

- Battery shop reconditioning at 30 days if used for engine starting, 60 days if used for standby power.

- No requirement to check voltage regulator setting.

NASA-Langley
- No operator requirement to check water per Memo No. 59 (Reference 5).

- Battery shop capacity check at 90 days from installation or 120 days from last check.

Marathon Battery Co.
- Operator checks water at 50 flight-hours for first 2 months, thereafter schedule is adjusted to fit operating conditions per Marathon Battery Instruction Manual.

- Battery shop capacity check based on user's experience (range: approximately 50 to 200 flight-hours).

- Check voltage regulator setting at periodic intervals (no time frame specified).

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*Capacity check refers to a 1C discharge to 19 V (19-cell battery) in prescribed time for particular battery under test, i.e., 34 amp-hr battery must provide 34 amps for 1 hour to 19 V. (C = battery capacity rating. A 1C discharge rate for an 11 amp-hr battery = 11 amps)

[3] NAVAIR 17-15BAD-1, *Operation and Maintenance Instructions With Illustrated Parts Breakdown — Naval Aircraft Storage Batteries*, Naval Air Systems Command, Washington, D.C., 15 January 1975.

[4] Technical Order, TO 8D2-3-1, *Operation Service Repair Instructions, Aircraft Nickel-Cadmium Storage Batteries*, Department of the Air Force, Washington, D.C., 1 April 1970.

[5] NASA-Langley Memorandum 59, *Aircraft Nickel-Cadmium Battery Maintenance*, National Aeronautics and Space Administration, Langley AFB, Virginia, 1 May 1978.

General Electric Battery Co.	•	Operator checks water at first 50 flight-hours, thereafter at intervals based on experience per Application Engineering Handbook.
	•	Battery shop capacity check at first 100 flight-hours, thereafter at intervals based on experience.
	•	Frequency of voltage regulator setting not cited.

Not only do the servicing intervals vary greatly, but the procedures for performing these servicings also vary. Electrolyte level checks, battery reconditioning procedures, and voltage regulator settings are examples.

Electrolyte Level Check

- The Army requires an in-aircraft check if access permits. Aircraft is run until battery is fully charged. Battery is then rested from 30 minutes to 2 hours. If water is visible above baffle at bottom of filler well, battery continues in service. Operator is not permitted to adjust water level. During 120-day/100-flight-hour check in battery shop, water is adjusted to 1/4 inch above the baffle at the bottom of the well after the battery has been fully checked and allowed to rest for 30 minutes minimum, 1 to 2 hours maximum, depending on the battery being checked.

- The Navy does not require operator to check water level. Battery is checked for proper level only in battery shop during 56-day check. Water level is adjusted to 1/4 inch after fully charging and rest for minimum of 12 hours.

- The Air Force does not require operator to check water. During 30-day check at the battery shop (60 days for standby power), battery is fully charged and water level is adjusted to 1/8 inch above baffle after rest of 2 hours minimum and 72 hours maximum.

- NASA-Langley does not require operator to check electrolyte level. Battery is checked for proper level in battery shop at 90-day intervals. Level is adjusted to 1/8 inch above baffle in bottom of well after full charge and rest for 2 to 4 hours.

- The Marathon Battery Company recommends the following electrolyte level adjustments. After fully charging the battery, adjust to 1/8 inch above the baffle at the bottom of the filler well. If time does not permit, adjust to 1/4 inch above baffle immediately after charge.

- The General Electric Battery Company recommends the following electrolyte level adjustments. After fully charging the battery, adjust to 3/8 inch above baffle after 2 to 4 hours rest (low-maintenance cells with their larger water head space should be

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adjusted to the hole in the top baffle). If time does not permit, adjustment can be made to 1-1/4 inch from top of cell at end of charge or overcharge.

- The American Electricians' Handbook cites the following electrolyte adjustment procedure. After full charge, adjust level to a maximum of halfway between the baffle and the inside of the cell cover, and a minimum of 1/2 inch above the baffle.

Reconditioning Procedures

- The Army requires a deep-cycle reconditioning of the battery during the 120-day/100-flight-hour check in the battery shop. This is a complete discharge procedure to zero volts per cell. The battery is usually shorted-out overnight to insure that all charge is removed. This is followed by a complete charge, and capacity check to determine whether the battery can deliver its rated capacity. The deep-cycle discharge is repeated until rated capacity is regained. The battery is usually scrapped or bad cells are replaced, as required, if rated capacity is not regained within three deep-cycles. Based on battery usage at Fort Eustis, approximately 4 to 6 years of service can be expected from a battery if proper maintenance is performed throughout its life.

- The Navy does not routinely deep-cycle a battery that is received at the battery shop for their 56-day check. Instead, the battery capacity is checked. If sufficient capacity is available, the battery is returned to service.

- The Air Force, like the Army, requires a deep-cycle reconditioning during the 30-day (60 days for secondary power batteries) check at the battery shop.

- NASA-Langley requires only a capacity check during shop servicing. If the battery produces 100% capacity or better, deep-cycle discharge is not accomplished. A deep-cycle reconditioning is accomplished only if the battery fails its capacity check. This is in line with the Navy procedure.

- The Marathon Battery Company recommends that the battery capacity be checked first, and the deep-cycle process be accomplished only if the battery fails to provide at least 85% of its rated capacity. 85% and above is acceptable performance for return to service.

- The General Electric Company also recommends that the battery capacity be checked prior to making the decision to deep-cycle. General Electric implies that 100% or greater capacity is required for return to service; however, their battery maintenance publication states: "Any battery having a discharge time less than acceptable should be given a reconditioning cycle."

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Voltage Regulator Setting

- The Army requires a weekly/25-flight-hour check for carbon pile regulators, or a 120-day/100-flight-hour check for solid-state regulators. The voltage setting is dependent on operating temperature, and is set using the weekly mean ambient ground level temperature. The new general battery maintenance manual, TM 11-6140-203-14-2, directs the operator to refer to the aircraft maintenance manual for voltage setting values. The aircraft manuals generally require the following settings:

Temperature	Voltage
Above 80°F	27 ± .2V
32°F to 80°F	28 ± .2V
Below 32°F	28.5 ± .2V

Some aircraft manuals, however, refer the operator back to the general battery manual for proper values (the CH-54 for example). This practice evolved from the old general battery manual, TM 11-6140-203-15-2, which cited the following voltage regulator settings:

Temperature	Voltage
Above 80°F	26.5 to 27.5V
32°F to 80°F	27.5 to 28.5V
Below 32°F	28.5 to 29.5V

- An informal check with the Navy and Air Force indicated that they do not routinely check the voltage regulator setting. A few operators have generated local procedures based on their own requirements and operating conditions. The Navy did provide the following recommended settings:

Temperature	Voltage
Above 80°F	27.5 to 28.50V, nominally 27.75V
32° to 80°F	28.0 to 28.5V, nominally 28.25V
Below 32°F	28.5 to 29.0V, nominally 28.75 V

In many instances, the Navy and Air Force aircraft dc bus voltage is fixed by a nonadjustable voltage regulator. No temperature compensation is provided with these regulators.

The above information highlights the differing maintenance requirements that have evolved based on a constant potential charge technique. This technique inhibits the establishment of a proper maintenance schedule. The ever-present threat of thermal runaway associated with the non-temperature-compensated dc bus requires, and justifiably so, that extreme caution be exercised when establishing servicing intervals. In many cases, maintenance personnel consider these requirements overly demanding, and disregard them completely. This invites trouble if a combination of overvoltage and overtemperature should develop inflight. The logical solution to this problem is a standardized maintenance schedule, based on the maximum time between maintenance actions that can be realized by using an on-board charger that conditions the dc bus into a temperature-compensated constant-current charging source.

APPENDIX D
NiCAD BATTERY PERFORMANCE CHARACTERISTICS

The sintered thin-plate, vented-type nickel-cadmium battery is used exclusively in Army aviation as the main source of engine starting and emergency standby power. The attractiveness of this electrochemical power source stems from its ability to provide high discharge amperage at very low ambient temperatures. A listing of the assets associated with this power source includes:

- Rugged construction for long life and reliability.

- Long storage period without deterioration in any state of charge.

- Can be recharged quickly (less than 1 hour from a deep depth-of-discharge).

- High discharge performance over a wide temperature range.

- Long cycle life.

- Can be overcharged for long periods without damage.

- Discharge voltage is nearly constant.

- Available in capacities ranging from 0.6 to 360 amp-hr.

- Charge retention is excellent.

- Resistant to shock, vibration, and physical damage.

- Resistant to damage due to current reversals.

The disadvantages of the NiCad battery are: unless properly charged, thermal problems may be encountered; the battery is relatively expensive when compared with the lead-acid battery. Comparative figures of merit for the NiCad versus other batteries are shown in Table D-1.

The nickel-cadmium battery is an electrochemical accumulator that works on the oxidation-reduction principle. A chemical reaction involving oxidation-reduction is one in which electrons are transferred from one atom or molecule to another atom or molecule. Oxidation involves an increase in oxidation number and an increase in valence state. The valence state of a material is increased by the removal of electrons from that material. Thus, oxidation involves the removal or loss of electrons. Reduction is the opposite reaction to oxidation, and involves the gain of electrons in a material. Oxidation-reduction reactions must occur together and must exactly compensate each other. The plate materials used in the nickel-cadmium battery can be readily oxidized or reduced. During the process of oxidation-reduction at the NiCad plates, electrons are transported internally from one plate to the other by an electrolyte solution, and externally by the circuit in which the battery is operating.

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TABLE D-1. COMPARATIVE SURVEY OF DIFFERENT BATTERY SYSTEMS

System	Energy Density	High-Rate Discharge Properties	Low-Temperature Properties	Internal Resistance	Charge Properties	Amp-hr and Watt-hr Efficiency	Charge Retention	Life	Mechanical Properties
Ni-Cd pocket, vented	2	4	5	4	5	1	4	5	5
Ni-Fe	3	2	1	1	4	3	1	5	5
Ni-Cd sintered, vented	3	5	5	5	5	3	3	4	5
Ag-Zn vented	5	5	3	5	2	5	4	1	4
Ag-Cd vented	4	3	5	2	3	5	4	3	4
MnO_2Zn	1	1	3	3	2	3	5	1	4
Ni-Zn	4	4	4	5	3	4	3	2	4
Ni-Cd sintered, sealed	3	5	4	5	4	1	1	4	5
Ni-Cd pocket, sealed	2	2	3	4	2	2	3	3	5
Ag-Zn sealed	5	4	3	4	1	5	4	1	4
Ag-Cd sealed	4	3	4	2	1	5	4	3	4
Pb-acid, pasted	3	2	2	4	3	5	1	3	1
Pb-acid, tubular	3	1	2	2	3	4	1	4	1
Pb-acid, Plante	1	1	2	2	3	5	1	4	1

A higher value indicates a better performance. The values used for figure of merit range from 1 to 5.

SOURCE: S. U. Falk and A. J. Salkind, ALKALINE STORAGE BATTERIES, John Wiley and Sons, New York, 1969, p. 434.

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In a charged state, the positive plate's active material is nickel oxyhydroxide (Ni OOH). On discharge, this positive active material acquires electrons (reduces) from the external circuit and gives up electrons to the electrolyte. As discharge continues, the positive active material reduces from Ni OOH to nickel hydroxide (Ni OH). At the same time, the negative plate material is converting from metallic cadmium (Cd) to cadmium hydroxide (Cd OH). This is an oxidation reaction where the negative plate is giving up electrons (oxidation) to the external circuit and acquiring electrons from the electrolyte. When the discharge ends and charge begins, the reactions reverse themselves with the positive plate oxidizing the Ni OH back to Ni OOH, and the negative plate reducing the Cd. OH back to Cd. The internal electrolyte conductor is a solution of potassium hydroxide (KOH) in water. The solute (KOH) readily disassociates in the solvent (H_2O) to form ions of K^+ and OH^-. Concentration of the electrolyte solution is approximately 31% KOH by weight. This relates to a specific gravity of approximately 1.3. Because the electrolytic solution acts only as a transporter of electrons, and does not take an active role in the plate reactions, its specific gravity does not change during the charge/discharge cycle. Consequently, a hydrometer cannot be used to determine the state of charge of a NiCad battery. This is the opposite of the lead-acid battery where the acid electrolyte is used up by the plates during discharge. The concentration of acid, and thus the specific gravity of the electrolytic solution, diminishes with discharge in the lead-acid battery. Thus, a simple hydrometer reading will reveal the state of charge in the lead-acid battery.

In addition to the plate material and the electrolyte solution, the plate separators play an important part in the overall NiCad cell reaction. The separator must perform two functions for the vented cell to work properly. First, it must maintain electrical insulation between plates of opposite polarity. Any internal shorts will render the cell inoperative. Secondly, it must act as a gas barrier to oxygen. This gas barrier is required to shield the negative plate from oxygen during charge and overcharge. The negative plate is trying to reduce (convert from Cd OH to Cd) when charging. If oxygen is allowed to migrate to the negative plate during charge, it will recombine with the metallic cadmium and full charge will be impossible. The recombination of oxygen at the negative plate will also produce large quantities of heat, which is damaging to the cell. The separator must, in addition to these two basic functions, provide minimum electrolytic resistance to the ionic flow of electrons between plates. Accordingly, the separator usually consists of a multilayered sandwich of materials with two layers of woven nylon to provide electrical standoff between plates, and one layer of cellophane to act as a gas barrier with good electrolytic conductance. New materials such as Permiom and Cellguard are now being used in place of cellophane because of their increased strength. The cells are also flooded with an excess of electrolytic solution so as to prevent oxygen from migrating to the negative plate. Any hydrogen and oxygen gas that is generated during charge or overcharge is vented overboard through the vent cap. These three features identify the vented cell NiCad battery: vent cap, gas barrier, and excess electrolyte.

The sealed cell NiCad does not have any of these features. In fact, the sealed cell works on the reverse principle, where oxygen recombination at the negative plate is necessary. That is, any gas (water) evolved during charge and overcharge is not vented overboard but recombined and retained within the cell. Therefore, water is not lost through a vent cap, an excess head of water is not required, and a gas barrier is not required or desired. Because the sealed cell does not require periodic water servicing, it is very attractive for aircraft applications. At present, however, sealed cell NiCad

batteries have two drawbacks: they can't be charged directly from the dc bus, and they cannot deliver the high discharge rates and high capacity that is associated with their vented counterpart. This means that their use is limited to light duty applications (not to engine start applications), and that a constant current charger must be used to safely charge these batteries. The charger must monitor the battery's voltage, pressure, and temperature to effectively charge the sealed cell. Overcharge current in excess of the 1C rate cannot be tolerated by the sealed cell. The charger must be capable of detecting exactly when the cell enters overcharge and reduce the charge current appropriately.

Basically, two techniques are available for charging the battery: constant potential (CP), or constant current (CI). CP charging is quicker than CI charging, and requires no external controls. The Army presently uses CP charging by applying the battery directly to the aircraft dc bus. The bus acts as a CP charging source, deriving its power from the aircraft generators. The bus provides a constant 28-volt source at current levels in excess of 300 amps. At deep depths of discharge, the large NiCad batteries used for turbine engine starting (batteries with capacity ratings of 22 amp-hr or 34 amp-hr) will draw in excess of 200 amps when first applied to the bus. Using the CP technique, a constant voltage is applied and maintained on the battery throughout the charge period. Typical CP charge cycles at different voltage levels are shown in Figures D-1 through D-5. The CP technique works on the principle of applied electromotive force (EMF) and back-EMF. Using CP, the EMF of the supply is greater than the back-EMF of a discharged battery. This difference between EMFs produces a current flow into the battery. The current flow is used to convert the active materials on the plates from a discharged state to a charged state. As charge continues, the battery's back-EMF increases, causing the charge current to diminish. When the back-EMF approaches the applied EMF, current flow approaches zero. Any increase in applied EMF, after current flow has minimized near zero, will cause additional current to flow into the battery until its back-EMF again approaches the applied EMF. The opposite is also true; that is, if the applied EMF is reduced, the battery will discharge into the charging source until the EMFs are again balanced.

The charge period progresses in three distinct phases. The first phase exists up to approximately 90% of full charge. The second phase exists from 90% to approximately 99% of full charge. The third is the overcharge phase. The battery acts differently in each phase. During Phase I, the battery readily accepts charge current. During this phase, active material on the plates is readily oxidized-reduced and little or no water is electrolyzed. During Phase II, the battery increasingly resists the flow of charge current. During this phase, unconverted active material becomes increasingly difficult to oxidize-reduce and the electrolysis of water into hydrogen and oxygen begins. During Phase III, all active material is converted, and any excess current forced into the battery is expended in the electrolysis of water. In overcharge, the water content of the electrolytic solution (KOH/H_2O) is reduced at a theoretical rate of 1 cc of water per 3 amp-hr of overcharge. This causes the specific gravity of the solution to increase, because the KOH factor does not change (except for minor expulsion of KOH as droplets in the venting gases), and requires the periodic servicing with pure water during maintenance actions. In addition, the water electrolyzes as hydrogen and oxygen gas at the negative and positive plates, respectively. Approximately 7 cc of hydrogen gas is produced for every amp-minute of overcharge. A 4% hydrogen atmosphere is very explosive. Accordingly, battery vents must be connected and free of obstructions so that these gases are expelled overboard. Excess overcharging in Phase III is not desirable. It does nothing for battery performance (capacity), and

boils off unnecessary amounts of water. The optimum charge scheme will stop charging when the battery reaches 100% of its full charge, i.e., when all of the plates' active material has been converted. It is necessary, however, to return more capacity to the battery on charge than was previously removed on discharge for this to be accomplished. If 10 amp-hr are removed from the battery during discharge, more than 10 amp-hr must be returned on the subsequent charge or the battery will not be fully charged.

This excess return charge is required to compensate for the battery's inefficiency. This inefficiency can be controlled if approximately 140% of the previously discharged ampere-hours are returned in charge at room temperature. The amount of required capacity return varies with temperature, charge rate, and other factors. A return of less than 140% capacity results in undercharge and weak batteries. A return of more than 140% capacity will not increase capacity, but will vaporize water unnecessarily. The proper amount of return capacity is critical to battery performance. The CP technique, although fast and inexpensive, is not very sensitive to capacity. The power supply charge voltage setting and the time available for charge will dictate the amount of capacity returned. Also, operating temperature influences the optimum charge voltage. If the temperature is high, lower voltage settings are required or excessive water boil-off will result. Low temperatures require high voltage settings or undercharge results. Consequently, charging from a non-temperature-compensated aircraft dc bus that can be inadvertently misadjusted by maintenance personnel affords only a remote possibility that 140% of the discharge capacity will be returned in charge. If a combination of high ambient temperature and high aircraft bus voltage is encountered (the worst possible condition for charging the battery), the excess water will quickly boil off, thermal problems will develop, and the battery will be destroyed. To prevent this from happening, the aircraft voltage regulator is set at a conservatively low value and the battery water level is checked at frequent intervals. This creates an unnecessarily heavy maintenance schedule for both water checks and low-capacity reconditionings. The CP technique is fast and inexpensive. However, based on the disadvantages cited above, the CI method of charging was developed so that better control over the ampere-hours returned to the battery could be realized.

As the name implies, the constant current charge technique converts the constant voltage provided by the aircraft's dc bus, and meters a preselected constant current to the battery regardless of its demand for more or less current. The CI technique is more expensive than the CP technique because electronic equipment (a charger) that converts the CP bus to a CI charge profile must be added to the charging circuit. The CI technique also takes longer to charge the battery because the initial high inrush of current that is characteristic of the CP charge is eliminated and replaced with the lower preselected current value. When the battery reaches 100% charge, however, the CI technique provides a means of controlling the ampere-hour return that is not possible with the CP technique. As can be noted in Figures D-1 through D-5, the battery voltage builds at a nearly constant rate until approximately 90% of full charge is reached. Between 90% and 100% of full charge the battery voltage exhibits a sharp rise, indicating that the active materials on both the positive and negative plates are approaching full conversion back to their charged state. After the 100% state of charge has been obtained, the battery voltage levels off in an overcharge plateau. If the power supply is set too low, as in Figure D-1, the battery will not reach the overcharge plateau. If the power supply is set at the plateau voltage, as in Figure D-2, overcharge current is very low and considerable time is required to return 140% of the previous discharge.
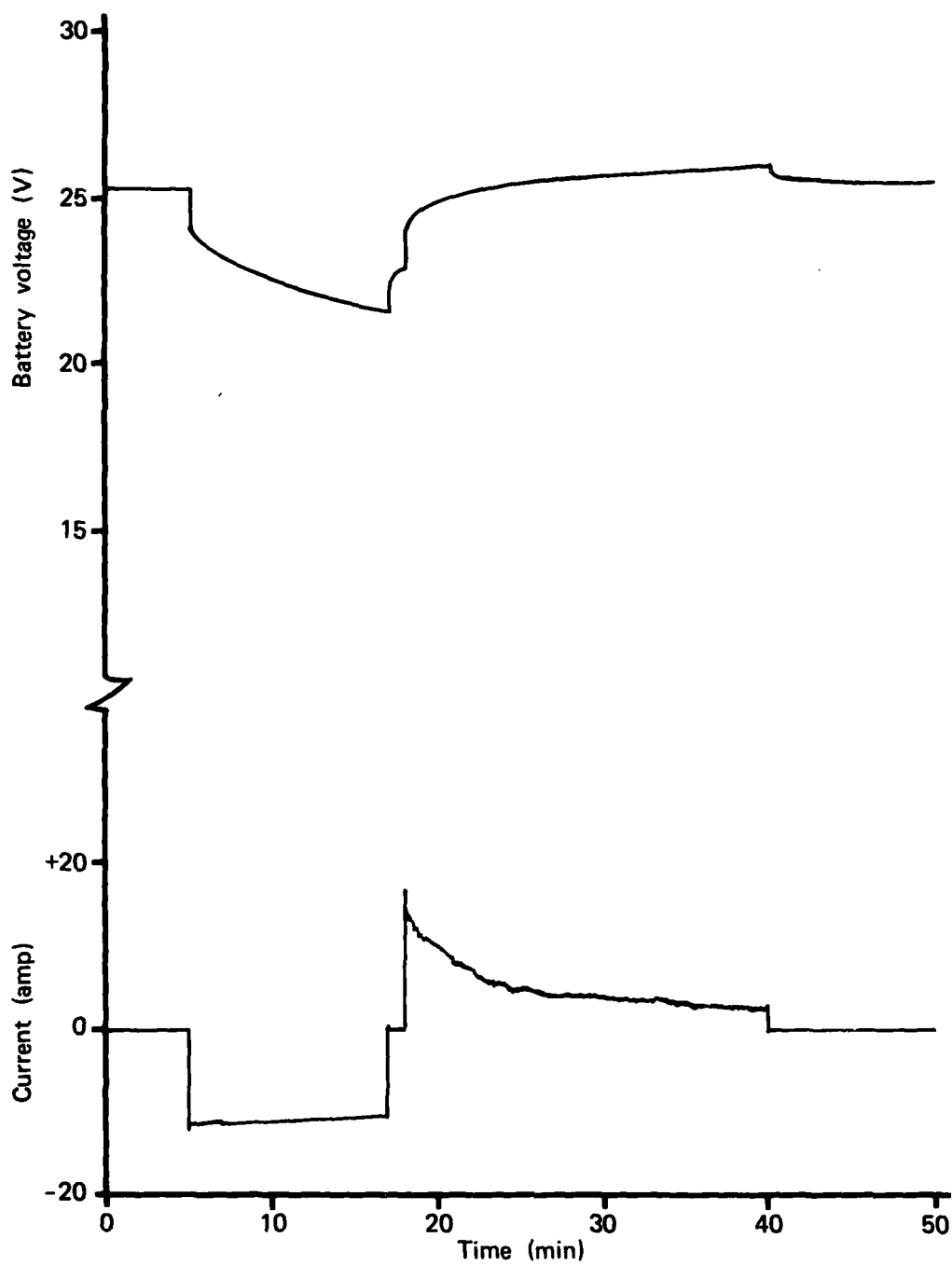
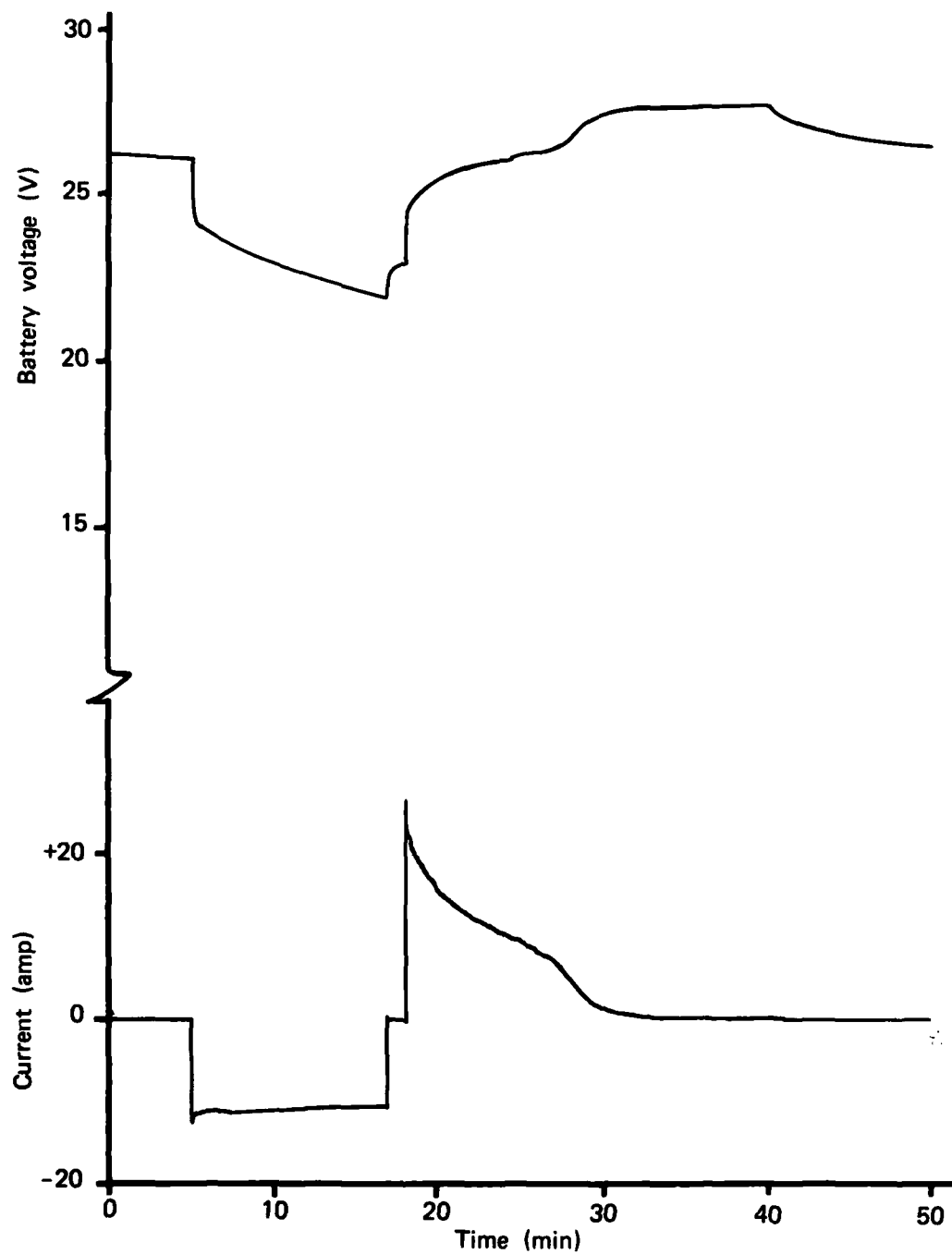Figure D-1. Battery voltage and current, constant potential charge — 26.7V.

Figure D-2.   Battery voltage and current, constant potential charge — 27.8V.
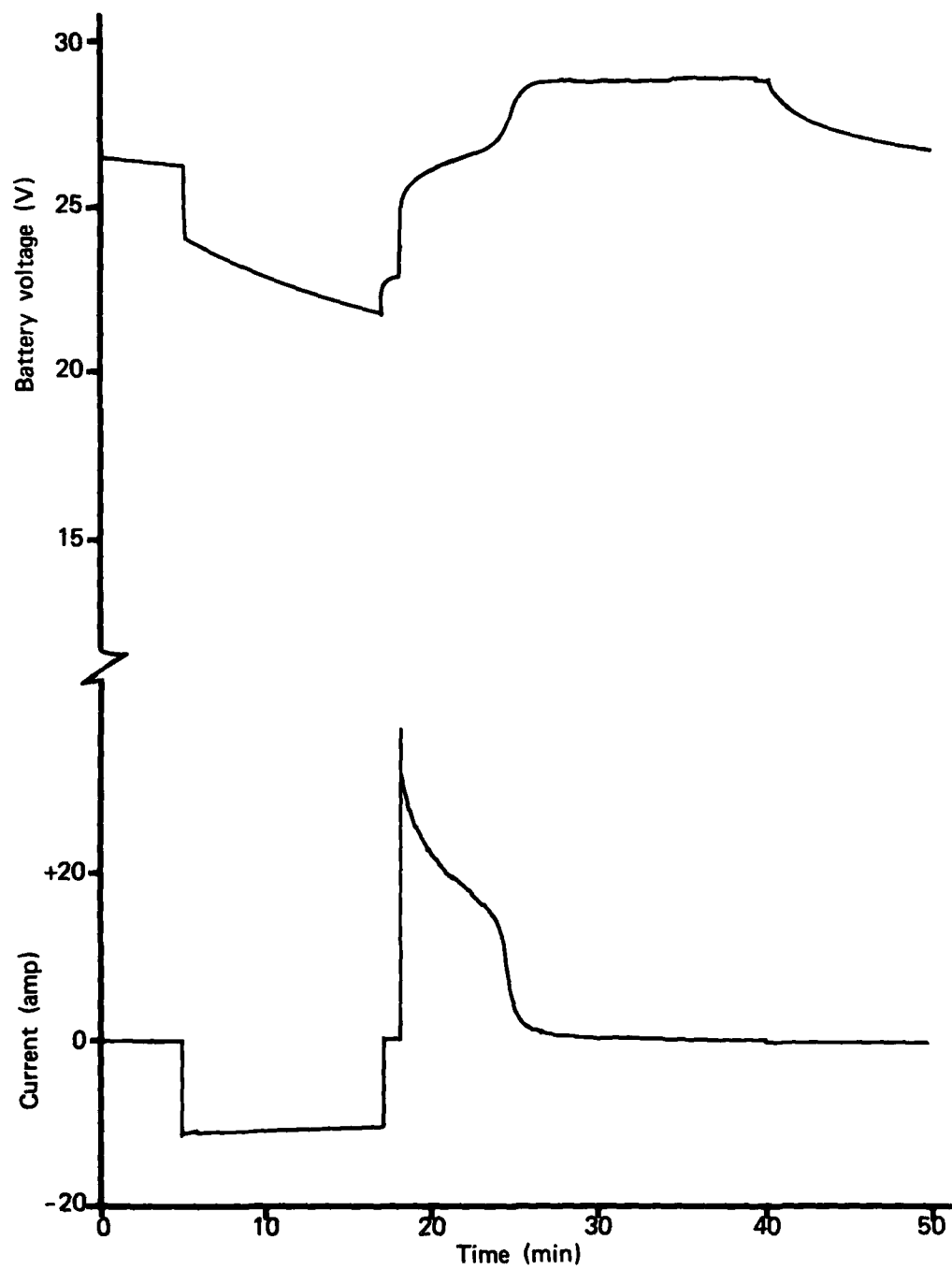
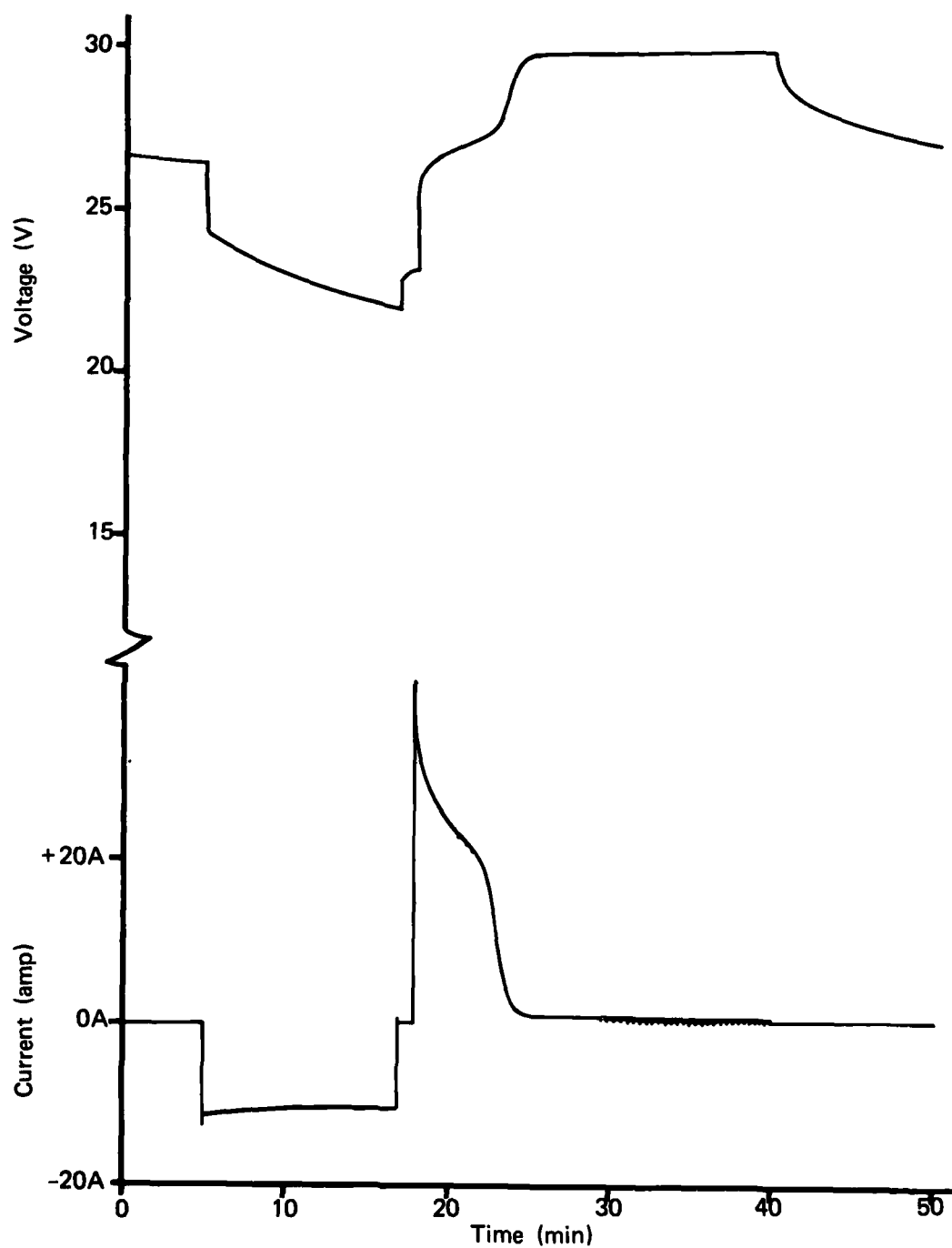Figure D-3. Battery voltage and current, constant potential charge — 29.0V.

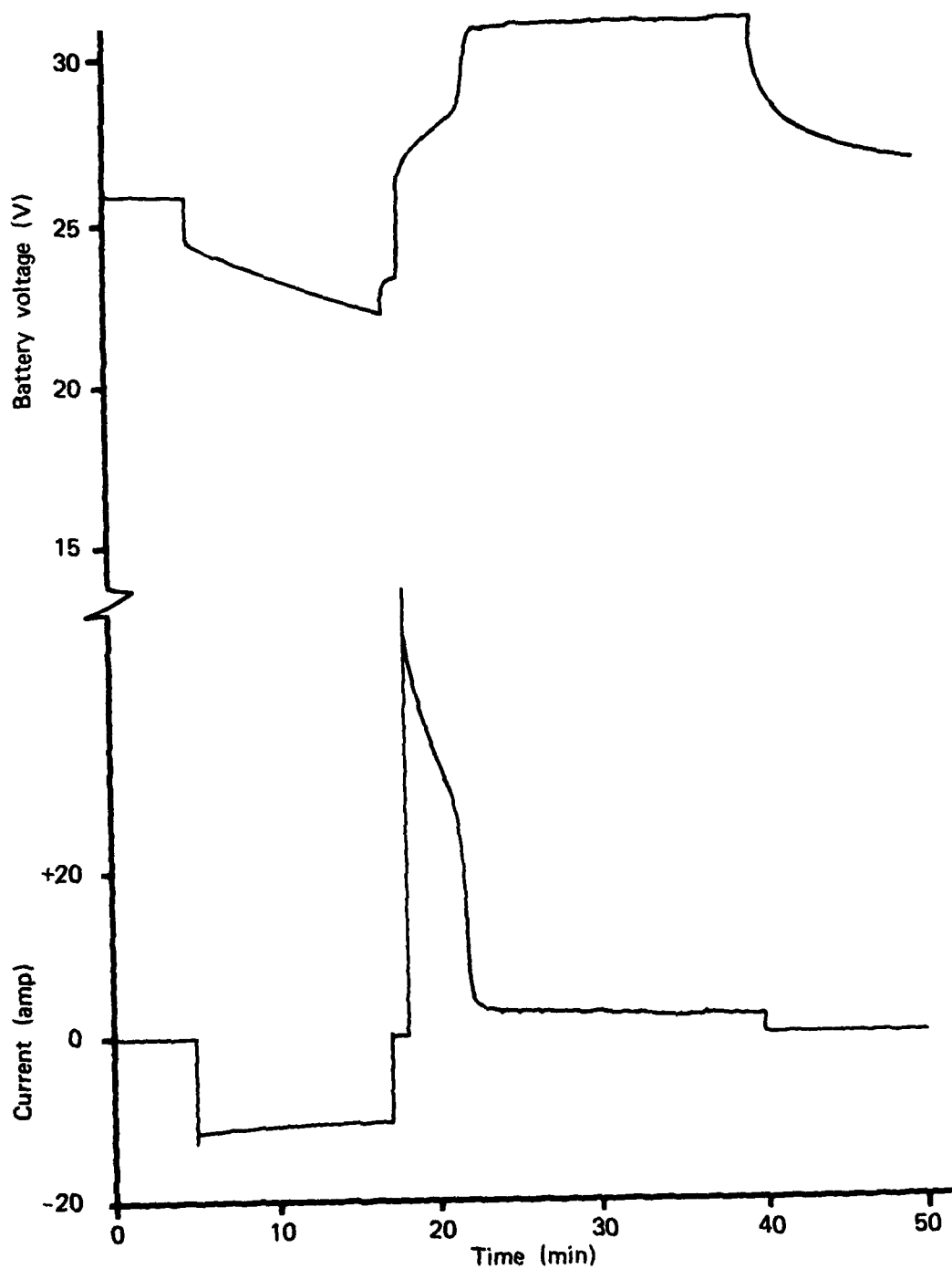Figure D-4.   Battery voltage and current, constant potential charge — 30.1V.

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Figure D-5. Battery voltage and current, constant potential charge — 31.6V.

Normal flight time is usually not sufficient for full charge at this low overcharge current. If the power supply is set above the plateau voltage, as in Figure D-5, overcharge is sufficient to return 140% of the previous discharge in less than average flight time. This is the principle upon which most on-board chargers operate. A constant-current charging rate is selected and applied to the battery by leading the battery's voltage with the power supply's voltage. The current rate is established by the equation

$$E_{P_S} = E_B + Ir,$$

where E_{P_S} =   power supply voltage

E_B =   battery voltage

I =   charge current

r =   internal battery resistance

To maintain a high overcharge current, the charger must boost the aircraft bus voltage into the 31 + volt range. The constant current is sustained by maintaining a constant voltage delta between the power supply EMF and the battery back-EMF. The proper amount of overcharge is returned to the battery by sensing when the battery voltage enters its rapid rise phase (approximately 28V) and by continuing charge for an additional 40% of the ampere-hours that have been returned to that point in the charge. This results in maximum capacity with minimum water usage.

The battery's capacity will diminish with usage in two modes: temporary capacity loss and permanent capacity loss. Temporary capacity loss can be eradicated through a deep-cycle reconditioning process where the battery is shorted out to zero volts and recharged to 140% of its rated capacity. This process ordinarily restores the battery to near its original rated capacity. However, as time in service increases, deep cycling is ineffective in overcoming the effects of permanent capacity loss. When not more than 50% of the battery's rated capacity can be reclaimed with three successive deep cycles, the battery is considered to be permanently unserviceable. With proper maintenance, permanent loss of capacity should be encountered after approximately 10 years of service.

In turbine aircraft applications, the battery must have the capability to accelerate the engine spool to start speed. A typical start profile is shown in Figure D-6. If the first start attempt is not successful, the battery should have a large enough capacity to afford two additional start attempts. Ordinarily, if a total of three attempts are not successful, the battery is dead and must be rested for a considerable period of time, or replaced, prior to another start attempt. Each start attempt discharges approximately 20% of the battery capacity. Accordingly, installation of a battery with less than 80% of its rated capacity available is not recommended. Below 80% rated capacity, three successive attempts to start will probably not be successful. High rate discharges affect the battery's capacity characteristics. For example, a battery with 100% capacity at the 1C discharge rate will deliver only 70-80% of its capacity when discharged at the 10 C rate (the C rating of a battery relates to its ampere delivery capability; that is, the 1C rating for an 11 amp-hr battery equals 11 amps). In addition to the rate of discharge, temperature also affects the battery's capacity capability. The capacity available as a function of temperature is shown in Figure D-7.
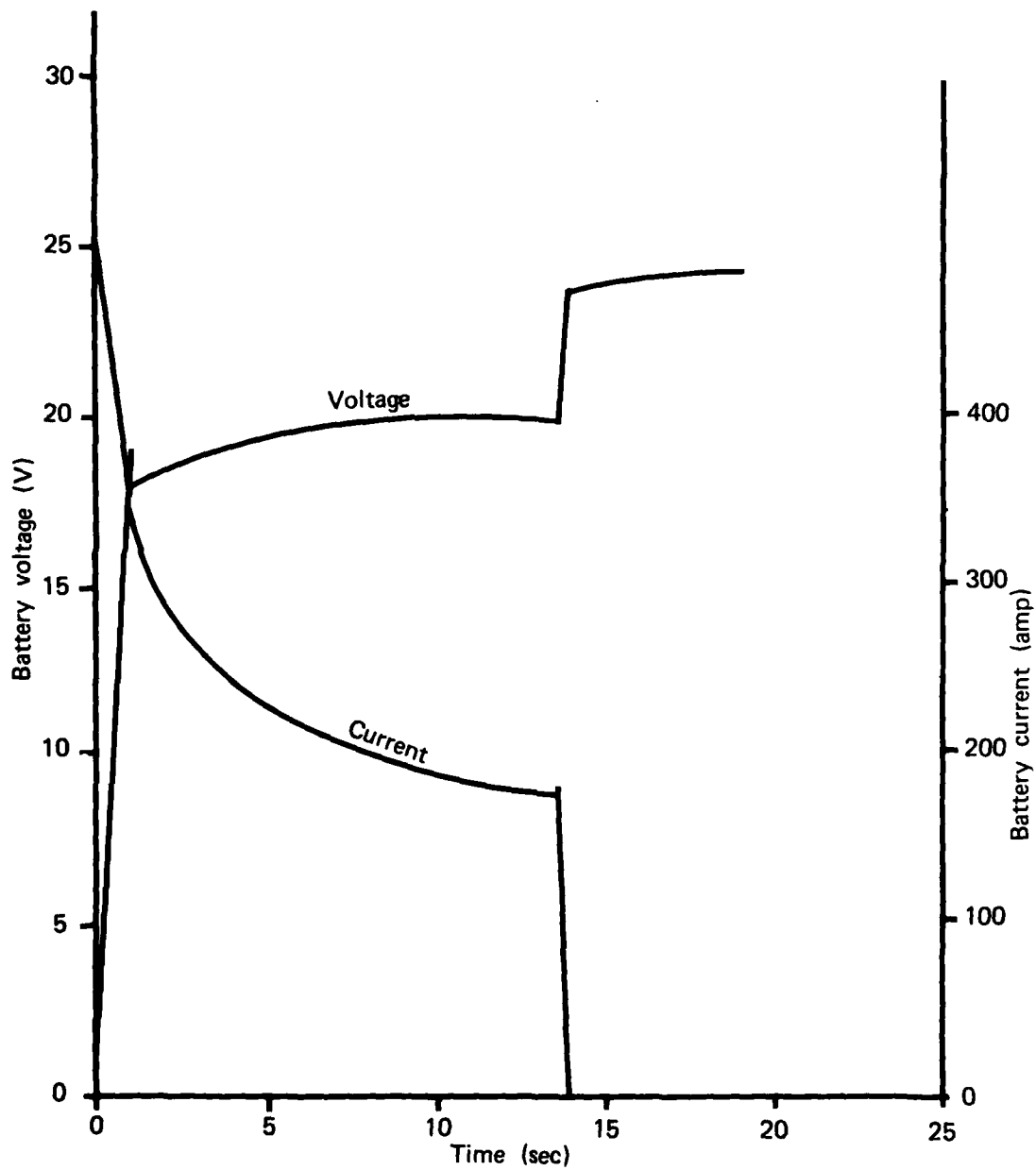
92

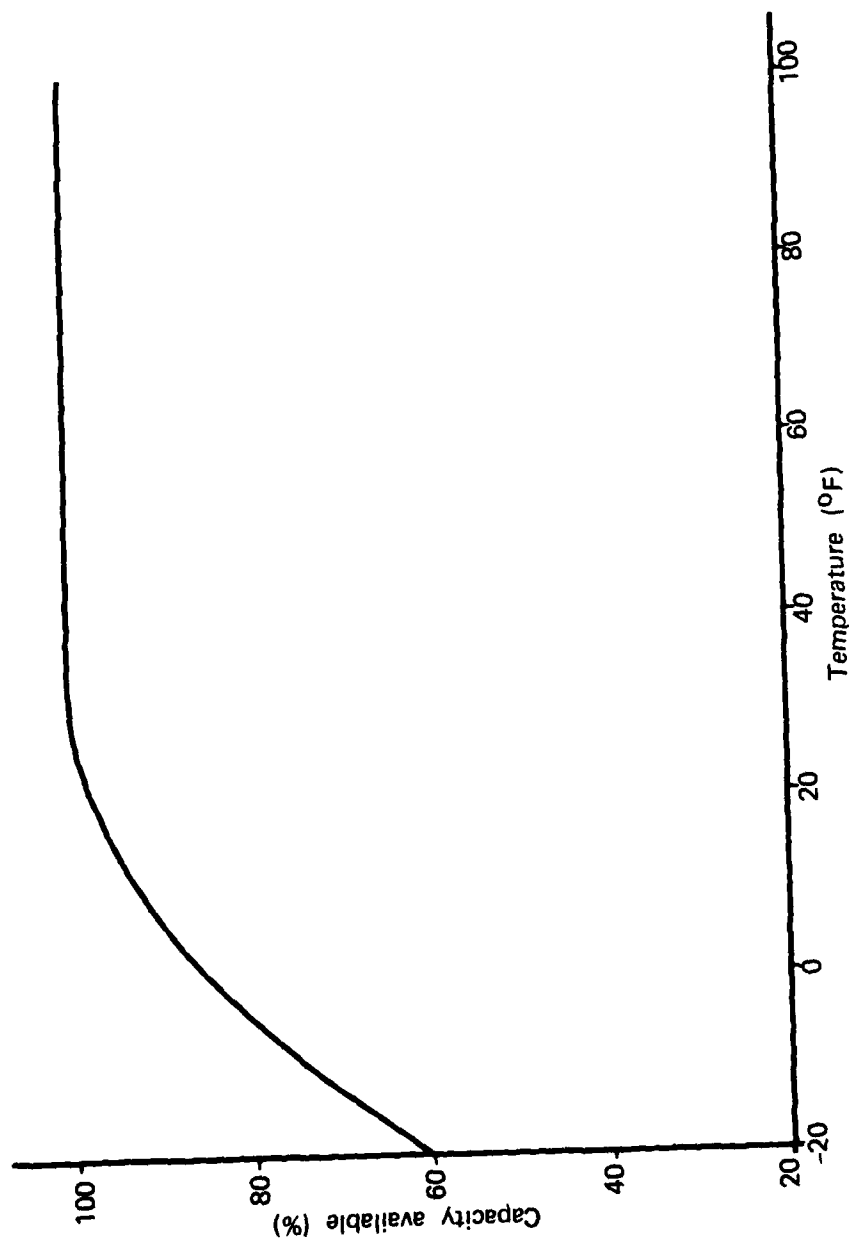Figure D-6. OH-58A start profile, 13 amp-hr battery.

Figure D-7. Temperature/capacity relationship.

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Under the best of conditions, an aircraft rated for a 22 amp-hr battery will require a larger battery installation (usually 34 amp-hr) if operating in a very low temperature climate. In addition, it must be remembered that the battery is used for emergency electrical power. If a third start attempt is successful, and an electrical failure is encountered shortly after takeoff, the battery may not have been charged for a sufficient period of time to provide the necessary standby power.

For these reasons, a battery is sized and maintained to a margin of power far in excess of a one-time start attempt. In addition to capacity characteristics, charge voltage and current have a dramatic influence on water usage. The BB-432/A batteries used in these tests have a water head space of approximately 2 inches. This space is available for excess water, that is, water above the plates. To just cover the plates with water, starting with a completely dry cell, approximately 14 cc of electrolyte is required. Once the cell has been filled to the top of the plates, each additional 1/2 inch of electrolyte added to the cell relates to approximately 14 cc of fluid. Accordingly, if the entire 2 inches of head space could be used, a total of 56 cc of excess electrolyte could be carried above the plates of each cell. This relates (using a 19-cell battery) to a total usable water volume of 1064 cc for the entire battery. If the electrolyte level is restricted to something less than totally full, because of possible spewing in overcharge or leakage in semi-inverted flight, the total usable water volume for the entire battery must be adjusted by subtracting 266 cc of water from 1064 cc for every 1/2 inch restriction below the 2-inch total. It is desirable to carry the maximum allowable water level so as to minimize servicing intervals, but too high a level that results in spewing is not tolerable. This test indicated that approximately 1 inch of excess water, measured at the end of charge, could be carried without adverse spewage or leakage effects. Existing Army publications limit the water level to not more than 1/4 inch above the plates. This appears to be a very conservative water limit, and may be resulting in excess servicing checks. It is imperative to keep the tops of the plates covered at all times. Uncovered plates not only results in poor battery performance which leads to battery damage, but also allows the oxygen to recombine with the negative plate, which is an exothermic process that leads to thermal problems.

The electrolyte solution must be maintained within a specific gravity range of 1.240 to 1.320. Gassing during overcharge will carry off droplets of electrolyte and thus reduce the specific gravity of the solution. As increasing amounts of pure water are added to replenish lost electrolyte, the battery's electrolyte solution may diminish to a specific gravity reading of 1.240. KOH should be added to the solution to return the reading to 1.30 if this condition evolves. Also, the electrolyte solution must be isolated from atmospheric CO_2. Atmospheric contamination is prevented by the one-way action of the vent caps. If a cap becomes clogged in the open position, or if the caps are removed for any length of time during water servicing, contamination will result. This will require a flush and refill with clean electrolyte solution.